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MIDAS

MOTORIST INFORMATION AND DRIVER AUTOMATION SYSTEMS

Final Report

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16. Abstract

This report investigates the feasibility, suitability and benefits of IVHS in Arizona. The report identifies travelers needs in each of four IVHS areas: Advanced Traveler Information Systems (ATIS), Advanced Traffic Management Systems (ATMS), Automatic Vehicle Control Systems (AVCS) and Fleet Management and Control Systems (FMCS). An assessment of the state-of-the-art technologies to meet these needs is presented within the context of an international review of IVHS related initiatives. Arizona's existing advanced technology programs are assessed including HELP, the Crescent Demonstration, and the Phoenix Freeway Management System. The suitability and potential benefits of IVHS development in Arizona are then presented by determining the integration and expansion of these programs into a broader IVHS initiative for the state. Key projects and milestones are identified for Arizona complementing and extending the national IVHS program. The framework for the development of IVHS in Arizona is presented in a statewide program for Arizona. Known as MIDAS (Motorist Information and Driver Automation Systems), the program plan is a ten-year IVHS initiative, initially focusing on traveler information and route guidance and moving toward highway automation concepts in the latter stages. The report outlines the program development, structure and proposed funding. An organizational structure for management and coordination of the program is also presented.

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METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	2.54	centimeters	cm
ft	feet	0.3048	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	6.452	centimeters squared	cm^2
ft^2	square feet	0.0929	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
mi^2	square miles	2.59	kilometers squared	km^2
ac	acres	0.395	hectares	ha
		MASS (weight)		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		VOLUME		
fl oz	fluid ounces	29.57	millimeters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.0328	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3

Note: Volumes greater than 1000 L shall be shown in m^3.

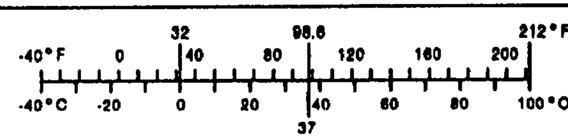
Symbol	When You Know	Multiply By	To Find	Symbol
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

These factors conform to the requirement of FHWA Order 5190.1A

*SI is the symbol for the International System of Measurements

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
yd	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
yd^2	kilometers squared	0.39	square miles	mi^2
ha	hectares (10,000 m^2)	2.53	acres	ac
		MASS (weight)		
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1000 kg)	1.103	short tons	T
		VOLUME		
mL	millimeters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1. THE MIDAS PROGRAM

1.1 Introduction

Traffic congestion is rapidly becoming one of the most serious problems affecting the U.S. highway network. Urban travel in general is increasing at a rate of four percent per year, but construction of new facilities is expected to accommodate less than one-fourth of this additional demand. Today, the 37 largest metropolitan areas in the United States are annually experiencing 1.2 billion vehicle hours of delay on freeways alone. Current predictions are for nearly a 50 percent increase in travel demand on urban freeways between the years 1984 and 2005. This would result in more than a 200 percent increase in recurring congestion and over a 400 percent increase in delay. Therefore, increased congestion and a continued loss of mobility are expected.

The projected growth in traffic is so great that traditional methods of road construction, demand management, and traffic control will not in themselves be satisfactory solutions. Only through an approach that captures the synergistic benefits of these traditional methods can we ensure traffic mobility in the future. Application of advanced technologies in areas such as motorist information and navigation systems, improved traffic control systems, and vehicle guidance and control systems has significant potential for relieving traffic congestion.

What is meant by advanced technologies in the context of easing traffic congestion? Loosely, we can group them under:

* Intelligent vehicles, in which advanced technology units operate independently on individual vehicles; and

* Intelligent highways, involving the installation of advanced technologies within the highway infrastructure.

In combination, these two categories form the basis of the Intelligent Vehicle Highway Systems (IVHS). IVHS also involves a significant degree of cooperation and integration of the on-vehicle units and the highway infrastructure.

A convenient way of grouping advanced technologies is by function. Four broad categories of advanced technology can be considered as follows:

* Advanced Traveler Information Systems (ATIS);

* Advanced Traffic Management Systems (ATMS);

* Advanced Vehicle Command and Control Systems (AVCCS); and

* Fleet Management and Control Systems (FMCS).

The concept of IVHS has been under study in Europe and Japan for several years. The United States is now poised to implement a major research, development and operational testing program to place these technologies on America's highways.

Recently, the U.S. Department of Transportation has published its National Transportation Policy (NTP). In this policy, Secretary of Transportation Skinner encourages the research and implementation of IVHS technologies. However, the Secretary adds that an initiative of this magnitude must be a genuine partnership between the public sector, the private sector and universities.

The State of Arizona is taking a lead in implementing this key aspect of the NTP by developing a statewide IVHS program to be known as MIDAS. This feasibility report addresses the initial elements of that program by preparing outline workplans for three of the IVHS technology areas: ATIS, ATMS, and AVCCS. The Arizona Department of Transportation (ADOT) is already recognized for its leadership in the FMCS area having successfully guided the Heavy Vehicle Electronic License Plate (HELP) program over the last six years. The results of these technology developments will also be incorporated in the Arizona IVHS project.

The following paragraphs briefly describe key features of the technologies included in ATIS, ATMS and AVCCS areas which are expanded in later chapters of this report.

Advanced Traveler Information Systems

Advanced Traveler Information Systems (ATIS) aim to provide motorists with in-vehicle information on congestion, traffic, weather, and highway conditions, and navigation, location or routing advice. ATIS will also provide pre-trip information, allowing drivers to plan their journey before leaving the home or workplace.

Many technologies exist which can provide the traveler with this information. Some systems rely on a direct communications link to an external infrastructure, such as vehicle location systems based on satellites, while others utilize radio broadcast transmissions. An alternative class of system is entirely self-contained in the vehicle and uses techniques like dead reckoning to compute vehicle position.

Specific types of ATIS include pre-trip electronic planning systems. With these, a traveler enters his origin and destination into a computer and a set of routing directions is produced. These directions can be based on minimum time, minimum distance or minimum cost routes. These systems also have strong potential for integration with transit information systems.

Traffic information broadcasting systems provide motorists with information on current highway conditions providing an opportunity to alter a route. Some systems, like the U.S. highway advisory radio, utilize conventional AM car radios but require the driver to retune to a specific frequency. Others use FM transmissions and self-tuning in-car decoders such as the West German ARI system and the Europe-wide Radio Data System.

In-vehicle navigation and location systems provide information through in-car displays. The most sophisticated systems, termed externally-linked route guidance, provide real-time information on traffic, road and weather conditions and provide appropriate route guidance to the motorists. These displays may show the highway network and the location of the traffic problems, allowing drivers to change routes and make more informed decisions, or may provide specific routing instructions.

Advanced Traffic Management Systems

ATMS are assumed to differ from traditional traffic control systems in two major respects. First, they are responsive to actual traffic flows and second, they operate in real-time. At present, control strategies react to congestion on the highway after it has occurred. An ATMS will incorporate algorithms that can predict when and where congestion will occur and will act to prevent it.

ATMS will include area-wide surveillance and detection systems. These provide information from the perspective of the overall highway network. ATMS will also integrate traffic control on the various facilities in an area. This implies collaborative management between the authorities responsible for managing both the freeways and the surface streets. Finally, ATMS will include rapid response incident management techniques, including incident detection, verification, and the implementation of appropriate response plans. Together this information is collected at a traffic control center, at which point truly optimal solutions to traffic problems can be developed for entire areas or regions.

The State of Arizona represents an ideal location for implementing ATMS technologies under diverse conditions. Maricopa County contains an impressive network of urban freeways, either new or currently under construction. Combined with a state-of-the-art freeway control center, this offers a major opportunity for evaluating various ATMS approaches. Additionally, the Phoenix surface streets and those in the city of Tucson provide opportunities to evaluate alternative technologies and to address the institutional arrangements needed to coordinate state and local government cooperation.

Advanced Vehicle Command and Control Systems

Vehicle control is complex because of the many interactions which exist between the driver and the vehicle. The driver's key roles can be defined as:

* to observe the outside environment, including highway geometry, vehicles and obstructions;

* to operate the vehicle's control system;

* to feedback observations and compensate for changing situations; and
* to decide and select an appropriate trajectory ahead.

One way to improve drivers' ability to cope with increasingly demanding traffic conditions more efficiently and safely is using intelligent driver support systems and automatic control devices. Automatic vehicle control systems can help drivers to perform certain vehicle control functions, and may eventually relieve the driver of some or all of the control tasks. The use of such technologies is likely to result in greater safety, more consistent driver behavior and improved traffic flow characteristics.

Basic research into automatic vehicle control technologies has been taking place for several years. However, recent technological advances mean that the stage has now been reached where these investigations should move into a more advanced, coordinated research, development and demonstration phase, targeted on system implementation within a defined timeframe. This reality has recently been recognized within a major study conducted for the national Cooperative Highway Research Program into the potential of advanced technologies to relieve urban congestion.

The Advanced Vehicle Command and Control System (AVCCS) is a concept potentially able to solve capacity problems on the nation's urban highways [1]. The objective of AVCCS is to automate vehicle operation on the highway. It will minimize the role of the human driver, utilizing a range of new and emerging technologies. AVCCS will integrate roadside traffic control systems with on-vehicle components and computer systems.

AVCCS is a most promising concept which could have a major effect not only on congestion and safety, but also on society's whole perception of automobile travel. However, there are still significant challenges to be met before the concept can become reality. The aim of this project is to take the first step on the road to meeting those challenges. It sets out a logical path forward which will allow the major potential benefits to be realized in a timely and efficient manner.

1.2 Objectives

This section defines the key objectives of this initial IVHS research study for the Arizona Department of Transportation. The overall objective of the project is to identify an Intelligent Vehicle-Highway Systems (IVHS) program for the State of Arizona. The program describes the role of ADOT in IVHS research, operational testing and implementation and defines the necessary relationships of ADOT with other public and private sector organizations.

1. Schmitt, L.A. Advanced vehicle command and control system. Journal of Transportation Engineering, vol. 116, no. 4, pp. 407-416, ASCE, July 1990.

To achieve this broad goal the following specific objectives have been addressed through the study:

1. Update existing literature reviews of IVHS technologies and the major national and international IVHS programs;

2. Consider the integration of other Arizona advanced technology programs, such as HELP, the Crescent Demonstration, and the Phoenix Freeway Management System, into a broader IVHS initiative for the state;

3. Identify suitable locations for the operational testing of the most promising IVHS technologies in the State of Arizona;

4. Define a proposed organizational structure for the Arizona IVHS program combining state and local government and private sector participation;

5. Define the reasons why the State of Arizona is an appropriate location for developing and demonstrating IVHS technologies;

6. Outline a series of IVHS activities to pursue through the Arizona program. These projects cover research, operational testing and implementation activities from the full IVHS technology arena and progress from a short-term through a long-term timeframe;

7. Prepare a preliminary analysis of the benefits to be derived from the various IVHS projects in the Arizona program; and

8. Prepare an outline proposal for funding the IVHS program, describing the estimated resources for the various IVHS activities and potential sources for obtaining these funds.

This initial feasibility report represents Project 1A of the MIDAS program. In accordance with the state's requirements of a one-month project undertaken with a restricted initial budget, the report makes maximum possible use of existing review material with only limited updating as required to reflect the fast pace of IVHS developments. Acknowledgement is made of other CRC research sponsors, including the National Cooperative Research Program (NCHRP) and the National Cooperative Transit Research Program (NCTRP), which provided substantial funding for the original compilation of much of the work presented in the review.

1.3 Research approach

This section outlines the approach taken by Castle Rock Consultants in initially defining an IVHS program for the State of Arizona. The research approach builds on the specific objectives defined in the previous section and identifies a set of specific tasks that were performed to accomplish the overall goals.

Task 1 Literature review

This initial task comprised a review of literature covering the major IVHS technologies and programs on an international basis. In order to accomplish this major activity within the extremely tight timeframe of the project, the work relied extensively on previous state-of-the-art reviews performed by CRC. The efforts in this project were focused on reviewing the most recent IVHS advances.

Task 2 Integration with Arizona advanced technology programs

Task 2 considered the integration of activities to be performed in the proposed IVHS program with other Arizona advanced technology initiatives. The State of Arizona is already a recognized leader in the practical application of new and emerging technologies and has major projects already underway that demonstrate this. This task aimed to identify the synergistic gains that can be accomplished by incorporating current efforts into the proposed program plan.

Task 3 Identify operational testing locations

In this task, the study team identified a number of locations within the state that can potentially be used to perform operational tests of IVHS technologies. Possible locations identified for IVHS operational tests include Crescent test sites; the Phoenix Freeway Management Center; the traffic control system in the City of Tucson; and the Ford Motor Company high-speed proving ground in Yucca.

Task 4 Define a proposed organizational structure

Task 4 prepared a proposed organizational structure for the Arizona IVHS program. The proposed structure was developed to reflect the management, technical direction and administrative needs of the future multi-strand IVHS initiative. Key participants who are expected to play vital roles in the proposed structure include state and local government representatives and the private sector. The federal government is also included, either as an active participant or in an overview role, depending on the ultimate shape of the program.

Task 5 Define why Arizona should implement an IVHS program

In Task 5, the research team prepared a series of clear and concise statements defining why the State of Arizona is an appropriate location for an IVHS program. These statements serve to highlight the strengths, experience and expertise resident in the state which will be important in the development and demonstration of IVHS technologies. Statements have also been developed which describe the benefits that Arizona will derive from a coordinated IVHS program.

Task 6 Outline IVHS projects and activities

Based on the products of the earlier tasks, the study team has developed a series of recommended IVHS projects and activities to be pursued through the Arizona program. These projects cover research, operational testing and implementation activities in the ATMS, ATIS and AVCCS areas. The activities span a short-term through long-term time horizon.

Task 7 Identify the benefits of the proposed IVHS projects

This activity builds directly on the work of the previous task. Task 7 defined the benefits of the projects included in the recommended IVHS program plan.

Task 8 Prepare funding proposal

This task developed an outline funding plan for the recommended Arizona IVHS program. The funding plan provides estimates of resource levels required for specific projects and activities, as well as for overall program management.

Task 9 Prepare final report

As the concluding task of this feasibility project, the research team has prepared this initial report on the work undertaken.

1.4 The next stages

The next stage of development of the Arizona IVHS initiative will set the MIDAS program into a broader systems framework. An important conclusion of this initial report is that MIDAS should form part of a wider multi-state initiative for cooperative IVHS development within a coordinated framework. This section outlines the recommended steps required to accomplish these goals.

The ENTERPRISE Initiative

The first recommendation of this initial study is that Arizona's MIDAS IVHS developments should be set within a multi-state cooperative program to be known as **ENTERPRISE AMERICA** (Evaluating New Technologies for Roads Program Initiatives in Safety and Efficiency).

ENTERPRISE AMERICA will provide a vehicle for practical coordination between interrelated state programs addressing distinct areas of IVHS. Participating states will jointly plan, develop and demonstrate IVHS innovation in areas of mutual interest. Each state will focus on an agreed area of excellence for in-depth systems research, demonstration and evaluation.

GALACTIC

In order to accomplish the overall liaison and coordination functions envisioned within the ENTERPRISE AMERICA initiative, a bridging project is proposed under the title of **GALACTIC** (Global Liaison and Coordination in Traffic Information and Control). As the name indicates, GALACTIC will address both international and interstate IVHS liaison activities.

These two aspects of the GALACTIC project can be summarized as follows:

* **Inter-Galactic**, addressing international cooperation and liaison between ENTERPRISE AMERICA and other worldwide IVHS programs. These include DRIVE and PROMETHEUS in Europe, plus VICS and SSVS in Japan.

* **Intra-Galactic**, dealing with the needs of joint planning, development and demonstration for the constituent state IVHS programs of ENTERPRISE AMERICA.

The Phase 1B project which is planned to continue the current effort will seek to further develop this initial report and set its recommendations within a multi-state program framework. Phase 1C will involve detailed planning and coordination of an initial meeting of ENTERPRISE AMERICA states, including follow-through with outreach materials and detailing of program activities.

1.5 Structure of this report

After this initial introduction, Chapter 2 presents a review of Advanced Traveler Information Systems (ATIS) IVHS opportunities. Chapters 3, 4 and 5 continue with reviews of Advanced Traffic Management Systems (ATMS), Automatic Vehicle Command and Control Systems (AVCCS), and Fleet Management and Control Systems (FMCS). Each chapter sets out to identify current developments and highlight areas with major potential for IVHS breakthroughs.

Chapter 6 goes on to outline the approaches taken by other IVHS initiatives worldwide. Chapter 7 looks at the integration of IVHS with other advanced technology initiatives in Arizona, and gives particular attention to potential IVHS test sites in the state. Chapter 8 defines a proposed organizational structure for the Arizona MIDAS program, while Chapter 9 sets out the major reasons why the state should implement IVHS, and presents an outline of proposed MIDAS projects. Chapter 10 identifies funding requirements and potential benefits of the different project areas. The last chapter includes a short summary and the conclusions of the initial project report.

2. ADVANCED TRAVELER INFORMATION SYSTEMS

2.1 Introduction

This chapter describes systems designed to provide drivers with information on highway conditions and route availability. Driver information systems can assist motorists in making decisions on appropriate route choice and in following the chosen route for a particular trip. Improved motorist route selection and route following should lead to more efficient utilization of the highway network, and consequent benefit to traffic as a whole.

Research studies carried out in the U.S. and Europe [1, 2, 3, 4, 5] have shown that many drivers are currently inefficient in selecting and following a route, for a variety of reasons. This inefficiency leads to excess travel, contributing to unnecessary congestion of certain routes and consequent wastage of resources which can amount to many millions of dollars every year in a large metropolitan area. Excess travel can generally be defined in terms of time, distance or cost, or some combination of these criteria.

Providing drivers with accurate information can help remove a proportion of excess travel caused by driver inefficiency in carrying out the three key trip activities of route planning, route following and trip chain sequencing.

Route planning takes place largely at the pre-trip stage. Conventionally, drivers plan their journeys either using maps or from information held in memory. Drivers can use any of a variety of route selection criteria, and are typically considered to allocate an "impedance" to each route, based on their personal criteria. The minimum impedance route is then selected for the trip being planned. Re-planning may take place en route as drivers become aware of traffic conditions, causing a conceptual change in the relative impedance of alternative routes. Inefficiency in route planning can be caused by inadequate attention to alternatives, or planning on the basis of inadequate or inaccurate information.

Route following involves implementation of the trip plan. This activity is conventionally aided by road signs and maps, to supplement drivers' recognition of their surroundings and sense of direction. Inefficiency in the route following task generally results in drivers losing their way, taking unplanned detours, or making other unnecessary deviations from their planned progress along a route.

Trip chain sequencing concerns complex trips which have multiple stops or multiple purposes [2]. Such a trip chain can incur significant excess travel if the sequencing of stops or trip segments is not optimized. Similarly, use of several single trips rather than a single, complex trip can result in a considerable amount of excess travel.

A number of approaches exist for assisting drivers in one or more of these activities by providing improved information. The remainder of this chapter covers the main approaches and describes previous experience of their use.

2.2 Electronic route planning

Sources such as maps or memory can, at best, only supply historic data on which routes are available. Supplementary information is required to describe transient road and traffic conditions, and to show which route is 'best' at any particular time. One possible solution to this need for additional real-time pre-trip information lies in the development of electronic route planning and information systems [6].

Electronic route planning systems link minimum path computer algorithms to highway network databases. Minimum paths can be determined in terms of journey time, distance or cost. Users access the route planning computer either directly or over a phone line, and see details of their optimum route displayed or printed out. Development of most electronic route planning systems has taken place within the last ten years. Some of the significant developments are described below.

In the U.S., an electronic route planning system has been developed by Navigation Technologies, Inc. (Figure 2.1). This selects destinations from a structured database, using a look-up table. The system has been used by rental car firms to provide customer directions.

In the U.K., a system known as AUTOROUTE is currently being marketed for route selection [7]. AUTOROUTE is a pre-journey route planner for microcomputers based around standard U.K. road maps. A route optimization module enables the system to identify a user's optimum route between a specified origin and destination. Optimization is based upon time, distance and operating cost according to parameters specified by the user. An abnormal routing module capable of considering traffic data from several sources is also currently being developed.

Electronic route planning facilities are also receiving attention elsewhere in Europe [8, 9]. The French TELETEL videotext system [10] comprises many interactive services including a route planning service called ROUTE. The service is accessed through remote videotext terminals which are connected by phone to service suppliers. The database for ROUTE contains network information, together with current data on highway maintenance and construction activities, road and weather conditions.

Also in France, the ANTIOPE service provides up-to-date traffic information which can be used by motorists in planning routes. ANTIOPE is not an interactive system, but collects and displays 30-40 pages of traffic information on a regional basis via a teletext TV service. ANTIOPE contains maps showing the congestion on major roads in selected areas which are updated at hourly intervals based on data collected by the highway patrol.

The U.K. Automobile Association (AA) has developed a similar service called ROADWATCH [11] which provides traffic information to radio stations, TV and teletext services. This networked system operates around a database which is kept up-to-date with the latest details of variations in road conditions due to weather, highway maintenance or accidents.

--FROM THIS LOCATION AT 1301 S 46TH ST RICHMOND
--TO SAN FRANCISCO INTERNATIONAL AIRPORT AT 1 SF AIRPORT TERMINAL LOOP SAN FRANCISCO
--ABOUT 26.8 miles, 44 MINUTES--
----------------Copyright 1987 K & C (SF2.0.7, 2.4.c)

Proceed E on 46TH ST.

Drive 0.1 miles on 46TH.
Turn RIGHT onto MEADE ST.

Drive 0.4 miles on MEADE.
Take I-580 SOUTH ramp to the LEFT.
Merge onto I-580 FRWY.

Drive 1.6 miles on I-580.
Take I-80 WEST exit.
Merge onto I-80 FRWY.

Drive 5.4 miles on I-80.
Continue onto SAN FRANCISCO-OAKLAND BAY BRIDGE .

Drive 5.2 miles on SAN FRANCISCO-OAKLAND BAY BRIDGE.
Continue onto I-80 FRWY.

Drive 1.7 miles on I-80.
Turn SLIGHT RIGHT onto US-101 FRWY.

Drive 11.3 miles on US-101.
Take SAN FRANCISCO AIRPORT exit.
Turn SLIGHT LEFT onto AIRPORT ACCESS RD.

Drive 1.5 miles on I-580.
Take BAYVIEW AV exit.
Turn SHARP LEFT onto BAYVIEW AV.

Drive 0.3 miles on BAYVIEW.
Turn SLIGHT RIGHT onto MEADE ST.

Drive 0.4 miles on MEADE.
Turn LEFT onto 46TH ST.

Drive 0.1 miles on 46TH to 1301 S 46TH ST RICHMOND.

Figure 2.1 Electronic route planning

At a pan-European level, there is a developing system known as ATIS [12] which aims to provide pre-trip information, both on road traffic conditions and on other aspects important to tourists. ATIS is based around the existing ERIC (European Road Information Center) facility, which is coordinated by the AIT (Alliance Internationale de Tourisme) in Geneva, Switzerland. Important traffic information is reported by the police and motoring organizations in each of 12 European countries to the Geneva center. Here it is processed and the resulting information transmitted back to each country, for dissemination via the motoring organizations.

2.3 Traffic information broadcasting systems

Traffic information broadcasting systems can potentially play an important role in keeping the motorist updated on current network traffic conditions, enabling him to adapt and re-plan his route as necessary. Systems can be used to warn drivers of various conditions including recurring congestion, short-term holdups caused by a traffic incident, or pre-planned activities liable to cause congestion such as highway construction and maintenance.

In the U.S. and Japan, traffic information broadcasting is provided by highway advisory radio (HAR). HAR is a short-range broadcast service provided to the motoring public through standard AM car radios [13, 14]. In the U.S., travelers' information stations (TIS) have been authorized to provide this service since 1977. HAR is operated by local and federal government agencies under rules that limit location, extent of coverage, and message content. This authorization and the rules covering HAR services are contained within Docket 20509 of Part 90 of the Federal Communications Commission (FCC) Rules and Regulations.

HAR stations can be authorized to broadcast on either 530 kHz or 1610 kHz, which are just below and above the standard AM broadcast band. Transmissions on these frequencies can be received by most standard AM car radio receivers, and the system therefore has the advantage that motorists do not have to purchase any special in-vehicle equipment. However, because of the localized nature of the service, motorists must be notified by appropriate signing when approaching an area serviced by HAR in order to tune their radios to the appropriate frequency (Figure 2.2).

In 1980 the Federal Highway Administration (FHWA) initiated a program to develop automatic highway advisory radio (AHAR) [15]. AHAR avoids the need for roadside signing and manual tuning by using a subsidiary FM receiver. This automatically mutes the car radio and tunes to the correct frequency (45.80 MHz) on entering the coverage area of the AHAR transmitter. The radio is retuned to its normal state after the message has been repeated and received twice. The system prototype was developed to the stage where it was technically proven, though institutional barriers have so far prevented the transition from HAR to AHAR.

Other traffic information broadcasting systems include the West German system known as ARI (Autofahrer Rundfunk Information) [16, 17], developed by Blaupunkt. ARI is widely used in Germany and parts of Austria, Switzerland and Luxembourg.

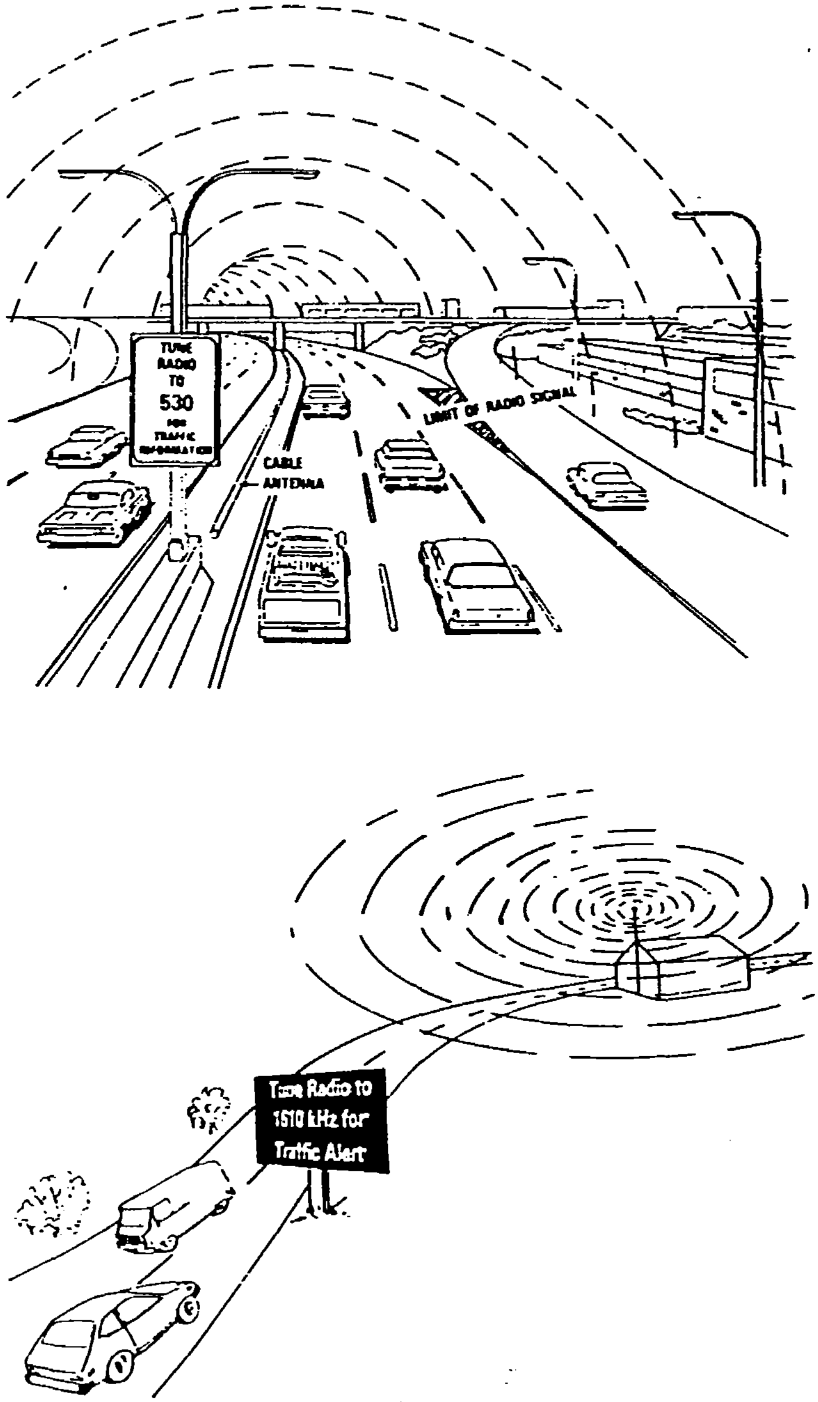

Figure 2.2. Highway Advisory Radio

(Source: Reference 13)

A modified version known as ARI-2 has also been implemented in parts of the U.S. [18].

In West Germany, traffic information is broadcast at specified times over a network of about 40 conventional FM radio stations, each transmitting on its own frequency. Because of the characteristics of FM transmissions, the range of each station is limited. With such a system using a large number of short range stations, it is important to provide a tuning aid to select the frequency of the station covering the area in which the motorist is traveling. The principal function of the ARI system is therefore to assist the motorist in tuning to a station which is providing traffic information, and to alert the driver when a traffic broadcast is imminent. To decode and utilize these ARI signals, vehicles need to be fitted with a specialized form of receiver. In West Germany, more than 80 percent of car radio receivers have an ARI capability.

The sources of traffic information for ARI are made up mostly of observations by police and highway agencies. The information flow process necessarily involves detection of a major change in traffic conditions and its cause; transmission to a radio station; and broadcasting to the motorist. This inevitably involves a significant delay, which can result in the information being out-of-date by the time it is received.

In an attempt to reduce this delay, an enhanced version of ARI has been developed called ARIAM [19, 20]. ARIAM stands for "ARI aufgrund Aktueller Messdaten," which can be translated as ARI with Actual Measurement. The objective of ARIAM is to automate the process of detecting changes in traffic conditions, disseminating that information to the public using the established ARI network. ARIAM uses automatic incident detection equipment as the main basis for detecting these changes. Initial tests of the system have shown that information about road and traffic conditions can be made available to the traffic control center and the motorist around 10-15 minutes earlier than a system relying on non-automated information collection.

A system which will eventually supersede ARI is the Radio Data System (RDS) of the European Broadcasting Union (EBU). This is a system which enables digitally-encoded data to be inaudibly superimposed on the stereo multiplex signal of a conventional FM broadcast. These data are decoded by a suitably-adapted car radio, which can automatically select the strongest of several traffic announcement programs when a driver leaves the reception area of one transmitter [21].

The Radio Data System has been under development by the EBU since 1974. It provides a unified standard for automated tuning, station identification and other receiver functions. The RDS Specification [22] was finalized in 1983, after coordination with radio receiver manufacturers confirmed that RDS objectives had been achieved. International efforts are currently taking place to develop standards for the RDS Traffic Message Channel (TMC). A specialized receiver is required to decode the traffic information, which can then be displayed either as text or synthesized speech. Such a system is particularly attractive from a European perspective because digital transmissions can be interpreted in the language of the driver's choice.

Studies are also being undertaken in countries outside Europe to investigate the possibilities of implementing RDS-TMC. These include Canada and Hong Kong. In the U.S., Chrysler has been carrying out trials of RDS traffic information in the Detroit metropolitan area.

Another traffic information broadcasting system of interest is EMERAUDE, developed in France [7]. This is based around the cellular radio-telephone system which will be installed over the entire French road network during the next ten years. The cellular system has been designed primarily for the transmission of personal voice communications, but has some spare capacity which will be used by EMERAUDE to transmit numeric data. This will include weather conditions, road passibility, traffic conditions and alternative route recommendations. Data will be collected by the police and road authorities, and will be updated on an hourly basis.

The onboard EMERAUDE equipment is a dedicated unit which receives, decodes and stores data. The driver can program the onboard unit according to the geographical areas in which traffic data are required. Data are passed on to the driver using a voice synthesizer, or can optionally be represented on an in-vehicle map display. The French telecommunications authority is currently in the process of implementing a trial of the EMERAUDE system in Paris.

While systems such as RDS-TMC and EMERAUDE are currently entering demonstration and field trial stages, however, a real-time in-vehicle traffic information system has already been made commercially available in London, U.K. [23]. The system, known as Trafficmaster, collects traffic information on major roads within a 35-mile radius of London using 115 sets of bridge-mounted infrared sensors. Detected congestion is broadcast to a portable in-vehicle unit using a VHF paging network. The screen on the receiver unit displays the motorway network with holdups pinpointed in red to allow the driver to make rerouting decisions. System portability allows the unit to be operated in the home or workplace to provide pretrip planning facilities.

The system manufacturer plans to extend Trafficmaster's area coverage to the British Midlands in 1991 and the complete U.K. motorway network by 1993. Receiver units can be purchased by users for approximately $860 with a $35 per month subscription charge. Message paging facilities can be provided for an additional $33 per month.

In the U.S., work is currently being undertaken by the Federal Highway Administration into the development of an in-vehicle safety, advisory and warning system (IVSAWS) [24]. This will provide an electronic extension of the driver's line of sight to warn of signs or hazards that are not clearly visible due to roadway curves, vegetation, poor visibility or other obstructions. The IVSAWS concept involves the use of radio transmitters mounted on regulatory and safety warning signs, on emergency or maintenance vehicles, or temporarily placed at roadway hazards. Upon activation, these would transmit short-range encoded messages to approaching motorists. Messages would be decoded by in-vehicle receivers and displayed to the driver, providing sufficient time for precautionary action to be taken.

2.4 Onboard navigation systems

Onboard navigation and location systems are a further area of motorist information technology. These systems provide the motorist with information on his current location and how this relates to his destination. In some cases, onboard navigation systems also provide advice on the best route to take. This information is calculated and presented by a self-contained vehicle unit, which does not require any external link to a roadside infrastructure.

Onboard navigation systems are generally of most use to the motorist in conducting the route following task. Systems which provide actual guidance information can also be used for the route planning task. However, without any information about real-time conditions on the traffic network, onboard navigation systems can only reduce motorist inefficiency which occurs under steady-state conditions.

A large number of self-contained vehicle navigation systems have been developed by manufacturers in the U.S., Europe and Japan. Several of these have passed through development stages but have not yet been implemented. Others have been tested on the highway and some are currently commercially available to motorists. The systems can be divided into the following three categories:

* directional aids;
* location displays; and
* self-contained guidance systems.

Directional aids typically use dead reckoning to provide navigational information to the motorist. Dead reckoning utilizes measurements made by distance and heading sensors to continuously compute a vehicle's location relative to a known starting point. Several different technologies can be used to monitor both distance traveled and vehicle heading [25]. The odometer is the most common approach for distance measurement. Heading sensors for dead reckoning include the magnetic compass and the gyrocompass.

Even the most precise dead reckoning systems accumulate error with distance traveled, and therefore require periodic reinitialization. Accuracies of around 2 percent of distance traveled are normally achieved. Reinitialization can be achieved in a number of ways, such as through a network of roadside proximity beacons, or by manual adjustment.

Proximity beacons work by local transmission of a location code, which enables a vehicle to learn its true current position. In practice, it may be uneconomic to deploy large numbers of such beacons purely for compensation of dead reckoning errors, and this approach is therefore not generally favored. Manual correction of the system position is required by some systems and has the advantage of being a low-cost approach. However, it reduces the utility of the system to the driver.

In-vehicle equipment for directional aids generally consists of a microcomputer, a keypad and a display unit [9, 26]. The motorist is required to enter position coordinates for his trip origin and destination. The vector connecting the two positions is then calculated and its characteristics (direct distance and heading) are displayed in the vehicle. Heading is usually displayed as an arrow symbol which identifies the direction the motorist should take in order to reach his destination.

The system continuously updates the vehicle position and recomputes the vector as the vehicle progresses on its journey. New headings and remaining distances are then displayed to the motorist. Therefore, as the motorist approaches each intersection on his journey, he has available both a measure of how near he is to his required destination and the direction he should take to reach it.

Location displays show the motorist his current position on an in-vehicle display unit, frequently in the form of a point on a map display. These systems have the distinct advantage over directional aids that the actual road network is indicated by the system. However, location display systems only show the driver where he is in relation to an intended destination, and do not offer advice on the best route to take.

Vehicle position in location display systems is calculated using initial coordinates updated through use of dead reckoning or trilateration techniques. Trilateration involves the detection of radio frequency (RF) transmissions from three or more fixed points. Ranges to those fixed points are then calculated, effectively fixing the position of the vehicle.

Land-based trilateration techniques include use of systems such as Loran-C [27] and Decca [28]. Loran-C has shown potential for vehicle navigation systems in the U.S. However, problems with Loran-C for this application include lack of coverage of the central U.S. (known as the mid-continent gap), as seen in Figure 2.3. Also, problems are encountered in receiving Loran-C transmissions in urban areas due to multi-path reflections and obscuration of the signals. Additionally, positioning accuracies are only of the order of 600 feet, which may be inadequate, particularly in urban areas.

Satellite trilateration techniques are currently based around the U.S. Navy TRANSIT system or the Navstar Global Positioning System (GPS). TRANSIT is a radio positioning system based on four or more satellites in approximately 600 nautical mile polar orbits, together with four ground-based monitoring stations [29, 30]. Ford's prototype TRIPMONITOR [31] system fitted in the "Concept 100" car in 1983 utilized TRANSIT, with a receiving antenna located in the trunk of the car.

TRANSIT, however, will shortly be superseded by Navstar GPS [32]. Navstar GPS is a space-based radio positioning, navigation, and time-transfer system that will become fully operational in the early 1990s. GPS has the potential for providing highly accurate three-dimensional position and velocity information along with Coordinated Universal Time to an unlimited number of suitably equipped users.

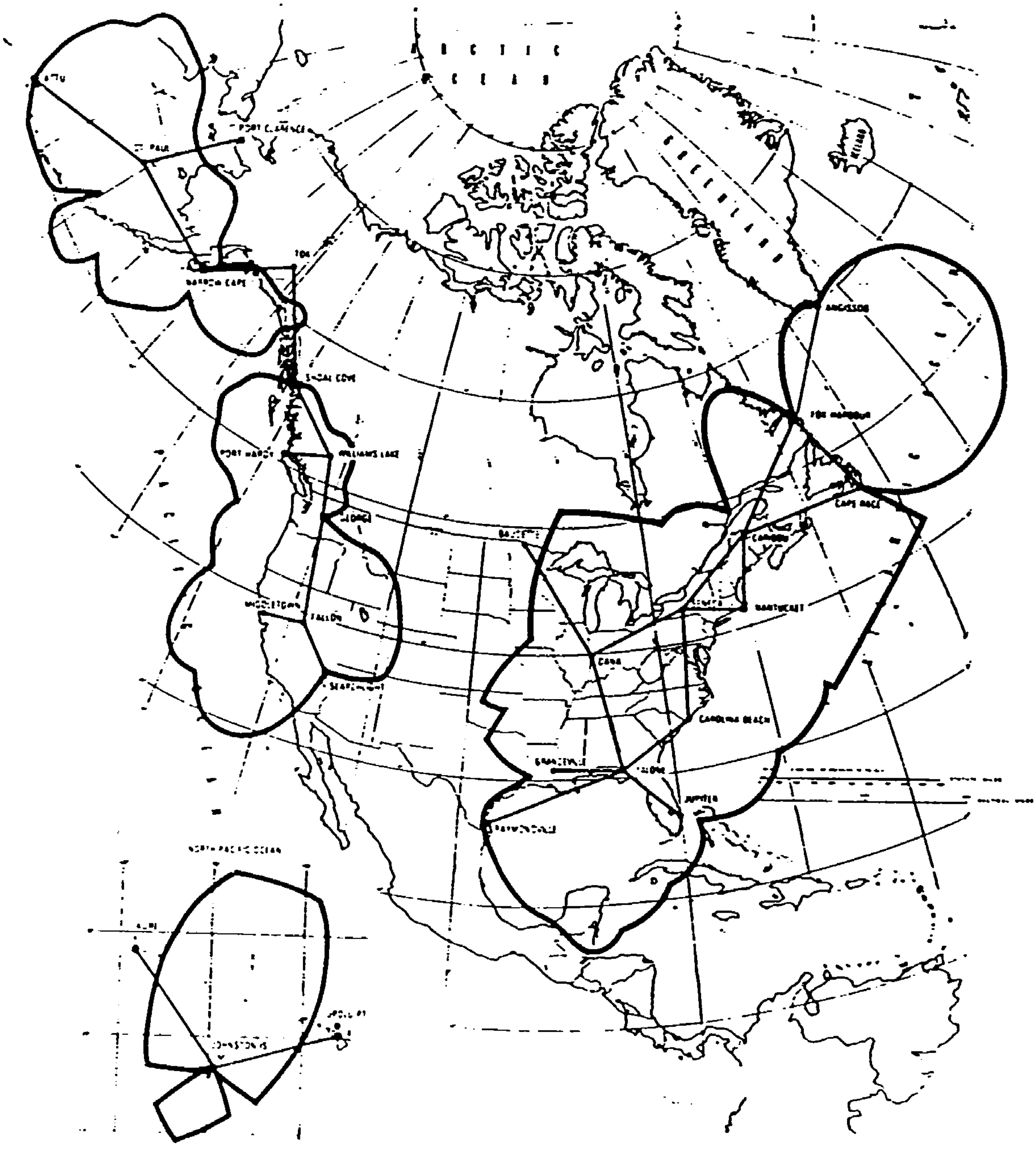

Figure 2.3 US LORAN-C coverage

(Source: Reference 27)

However, GPS is not without drawbacks [33]. First, GPS receivers are complex and costly. Second, signal disruption caused by tall buildings, tunnels and bridges leads to positioning discontinuities, particularly in built-up urban areas. Augmentation of GPS-based systems with dead reckoning capability is therefore necessary for a continuously effective onboard navigation system.

GPS has been considered as the basis of onboard location display systems by several manufacturers, including Chrysler, General Motors and Ford. Chrysler demonstrated its CLASS prototype system based on GPS at the 1984 World Fair [34].

At present, however, the market place for location-display onboard navigation systems is dominated by systems which are based primarily on dead reckoning (DR). One of the earliest successful attempts at producing a DR-based location display system is the Japanese Honda ELECTRO-GYROCATOR [35]. This device relies on a helium rate gyro to sense heading and an electronic odometer to dead reckon the position of the vehicle.

More sophisticated DR-based location display systems include the ETAK NAVIGATOR, Car Pilot and Philips CARIN. The ETAK system [36, 37] is the only onboard navigation system which has been actively marketed in the U.S. This uses dead reckoning augmented by map-matching to track vehicle location on a CRT map display. The ETAK system incorporates a flux-gate magnetic compass as well as differential odemetry for dead reckoning inputs, and uses compact disks or tape cassettes to store digital map data.

The map-matching augmentation of the dead reckoning system is based on the fact that vehicles are generally constrained to travel on the highway network. This makes it possible for algorithms to use a map as the basis for matching the pattern of the vehicle's indicated path (from dead reckoning) with that of the feasible path on the map, and so determine vehicle position at specific points where the pattern clearly changes, such as at a turn in the road.

In Europe, the ETAK system is currently being sold under license by Bosch-Blaupunkt, using the name Travelpilot. The system was launched in West Germany in May, 1990, and reportedly sold over 1,000 units within its first year. However, plans to introduce the system in France and the U.K. have been delayed after feedback from German users indicated insufficient network coverage. The German system contains only the autobahns, main routes and large towns. In contrast, the Travelpilot version available in the Netherlands has digitized maps for the entire Dutch highway network.

Competition for the Bosch Travelpilot will soon be provided in the form of the Dutch Car Pilot system. This is scheduled for official launch in the European market in January, 1991. Car Pilot will use wheel sensor-based dead reckoning and map matching techniques to establish vehicle location and desired destination. Road networks will be stored on CD-ROM, digitized from 1:10,000 maps and augmented by in-depth video data collection. CDs will need to be updated approximately every 6 months to reflect changes in the highway network.

The likely cost for the Car Pilot system is estimated at around $5,000. Optional enhancements will provide automatic vehicle location and route logging. This latter facility will enable vehicle location to be recorded for every map-match. The data will then be stored on floppy disk for subsequent route reconstruction.

The Philips CARIN system [38, 39] currently exists as a prototype version. This system uses a compact disk capable of storing 600 Mbytes of data, sufficient to hold a digital map of a very large area. For the future, Philips proposes that the system will provide actual routing instructions, and will be capable of using GPS for positioning as well as its current DR capability. Further development of CARIN is being undertaken as part of the European CARMINAT project within the Eureka framework, in a cooperative effort between Philips, Renault and Sagem of France.

Self-contained guidance systems provide the motorist with actual routing advice, as well as vehicle location information. To provide this routing advice, a more comprehensive description of the road network must be stored in the vehicle unit, together with an algorithm which can compute an optimum path through the network.

In some systems, such as ROUTEN-RECHNER, EVA, and ROESY, a description of the highway network is stored in memory in terms of the intersections (nodes) and the impedance of the road links which connect them. A suitable algorithm can then be used to compute the minimum impedance path between any two intersections. Distance is most commonly used as a measure of impedance, because it is the easiest to establish, but time or cost can be used as criteria for route selection if sufficient data are collected.

In other systems, the network description is pre-compiled to provide signpost data for each intersection, with the resolution needed to give guidance to every other intersection in the network. This pre-compilation process can employ a distance, time, or cost criterion.

Self-contained route guidance systems can again use dead reckoning or a trilateration technique as the basis for fixing the vehicle location. In each case the motorist must initialize the system by keying in codes for his required destination using a keypad. The system then computes the best route through the network using an appropriate minimum path algorithm.

Presentation of the routing advice to the motorist may be achieved through a variety of interfaces. These include alpha-numeric displays, graphic displays, speech synthesis units or other audio signals. Visual displays may either be located at dash panel level or may take the form of head-up displays, similar to those used in aircraft.

One of the earliest successful attempts at providing routing instructions to motorists via an in-vehicle system was ARCS (Automatic Route Control System), developed in the U.S. by French [40] during the early 1970s. This used dead reckoning augmented with map-matching to track the vehicle location. Routing advice was provided by pre-programmed audio instructions which were developed off-line during a pre-trip route planning process.

ROESY may have been the first system to develop routing instructions in the vehicle. This prototype allowed the user to specify a network of up to 300 nodes and 450 links, and to specify both the lengths and impedances of the links.

Origin and destination codes were then entered on the keyboard, and a speech synthesis unit was used to give routing instructions to the driver as he progressed on his journey. The device was not developed beyond the demonstration phase.

A similar principle was used by the German ROUTEN-RECHNER from Daimler-Benz [41]. This was primarily aimed at providing route guidance on the German autobahn network. ROUTEN-RECHNER used minimum distance as its criterion for optimum route selection and stored details of intersections and connecting roads in memory. The routing advice was presented to the motorist via audio messages or on an alpha-numeric display. As with ROESY, it was assumed that the driver followed the instructions implicitly, as measurement of distance traveled dictated the timing for displaying instructions.

Also in Germany, the EVA (Electronic Traffic Pilot for Motorists) system developed by Bosch-Blaupunkt [42] was developed specifically for metropolitan areas. EVA used dead reckoning and digital map-matching techniques to determine the vehicle position, and utilized this positioning information in giving appropriate instructions. Instructions were presented aurally via a speech synthesizer unit and also visually by a liquid crystal display unit.

In France, a prototype in-vehicle map display and routing system called DANA has been developed [7]. This uses road network data stored in an onboard computer to make recommendations on the shortest path to a desired destination. A visual display is used to provide turning instructions during a journey. DANA's location subsystem uses dead reckoning, with computer algorithms employed to minimize the deviation between the measured and the actual vehicle position.

Finally, Plessey has developed a self-contained route guidance system known as PACE (Plessey Adaptive Compass Equipment). PACE [43, 44, 45] is based on dead reckoning using an electronic compass to sense vehicle heading. This is coupled to a map database and minimum path software, with routing instructions presented on a small visual display panel. Plessey claims an accuracy of 1 percent of distance traveled.

2.5 Externally-linked route guidance systems

Externally-linked route guidance systems comprise all electronic route planning and route following aids which have a communications link from in-vehicle guidance equipment to an external system providing network or traffic information. The advantage of these systems over self-contained onboard navigation systems is that they can potentially take account of real-time traffic conditions, providing additional benefit to the motorist in conducting his route-planning and route following functions. The extent and usefulness of the real-time information provided depends on the particular system configuration under consideration.

Externally-linked route guidance systems can be divided into two main categories: those linked by a long-range communications or broadcasting channel to a traffic information service; and those with a short-range communications link to a roadside infrastructure. These are each described in the following paragraphs.

Long range communications systems are limited to receiving information on major traffic incidents or delays reported by police or highway agency personnel. They would be unlikely to take account of normal variations in traffic conditions, due to the absence of an effective monitoring network in recording transient traffic conditions. Possible approaches in this first category are route guidance systems which utilize mobile cellular radio, systems which are linked with RDS, and systems using digital broadcasting such as AMTICS.

Cellular radio [46] provides a mobile radio telephone service using a modular coverage plan. A cellular radio could be used in conjunction with a modem and onboard computer unit to interrogate a traffic condition database held on a remote computer. This database could be used to update versions of the digital map information held by an onboard route guidance unit, reflecting known changes in network conditions. Alternatively, the information could simply be presented to the driver to supplement information supplied by an onboard route guidance unit.

Coded network traffic information broadcast using RDS could also be used to update map databases held in memory by an in-vehicle unit, or again could be presented separately to the motorist as additional information. With RDS, the driver would not need to take any specific action to interrogate an information source, but would simply need to have the RDS receiver switched on. Information received from RDS would be stored in memory, updating previous data records.

A current Japanese initiative in long-range externally-linked route guidance has been set up by the Japan Traffic Management Technology Association. Proposals for the Advanced Mobile Traffic Information & Communication System (AMTICS) have been developed in cooperation with the Japanese Ministry of Posts and Telecommunications (MPT) and a number of private corporations.

AMTICS is an integrated traffic information and navigation system. Traffic information is collected by Traffic Control and Surveillance Centers managed by the police and located in 74 cities. The information is reprocessed at the AMTICS data processing center and then broadcast to vehicles. The broadcasting system is a radio data communication system called teleterminal. The equipment in vehicles will consist of a display screen, a compact disk read-only memory (CD-ROM) reader for retrieving map information, and a microcomputer to calculate the vehicle's position and to superimpose it on the display.

In 1987 a Conference on the Practicability of AMTICS was organized in which 59 private corporations participated. Twelve groups of companies have since joined together to develop elements of the system within an overall, coordinated framework. Within this framework however, each group of companies is pursuing its own system development program. An experimental system was started in Tokyo in 1988 and the first commercial system was made available in Tokyo and Osaka in 1990.

Short-range communications systems, which make up the second category of externally-linked route guidance systems, also include several different approaches [8]. These approaches are responsive to traffic conditions to varying degrees, and include both one-way and two-way vehicle-roadside communications. Some of these systems have been tested in the field, while others have not progressed beyond the conceptual development stage.

Data received by the in-vehicle unit from the roadside infrastructure are usually location parameters enabling the vehicle's position to be determined, and/or updates of road network and traffic conditions, which are used for route guidance purposes. In two-way systems, data sent from the vehicle may comprise vehicle type, destination and journey times over previous links of the network. This latter information is the essential feedback needed to realize the possibility of fully-responsive real-time route guidance.

At the simplest level, a basic "beacon" system configuration with low data rate roadside-vehicle communication provides similar benefits to a self-contained onboard route guidance system. This configuration operates by equipping key points on the highway network with data transmission beacons, which continuously emit unique codes identifying particular locations. Techniques include use of inductive loop, radio frequency, microwave or infra-red transmissions.

Vehicles must be equipped to receive and decode the beacon transmissions, and also need an in-vehicle unit comprising a keypad, a microprocessor, a display unit, and a map database. If beacons are very closely-spaced, no dead reckoning or other onboard location sub-system is needed. Alternatively, with less frequent beacons, a self-contained onboard route guidance system is required, with beacons serving to correct accumulated positional errors.

A second level of system complexity provides a limited degree of responsiveness to traffic conditions. In this configuration, rather than simply transmitting a location identifier code, each beacon transmits part of an electronic map, at high data rates. This is used by in-vehicle equipment to calculate route guidance advice, and avoids the need for each vehicle to carry a detailed map database for the whole network.

The highest level of route guidance system complexity provides a two-way communications link between the vehicle and the roadside infrastructure. The two-way link enables each vehicle to supply the infrastructure with journey time information on the section of network it has just traveled, as well as receiving information on alternative routes ahead. This floating car information is used by a central computer to update a continuously-changing model of network conditions. This model is used as the basis for supplying routing advice to motorists.

Systems which utilize two-way communications links in this manner are potentially able to operate in a fully-responsive mode, taking full account of changing traffic conditions. The advantage of this type of system over an onboard navigation system is illustrated in Figure 2.4. A self-contained onboard navigation system treats determination of the optimum route between two points as a two-dimensional problem, since the impedance along each link between the two points is assumed to be fixed. However, a fully-responsive route guidance system treats the journey between the two points as a three-dimensional problem, whose link impedances vary with time as network conditions change. Optimum routing

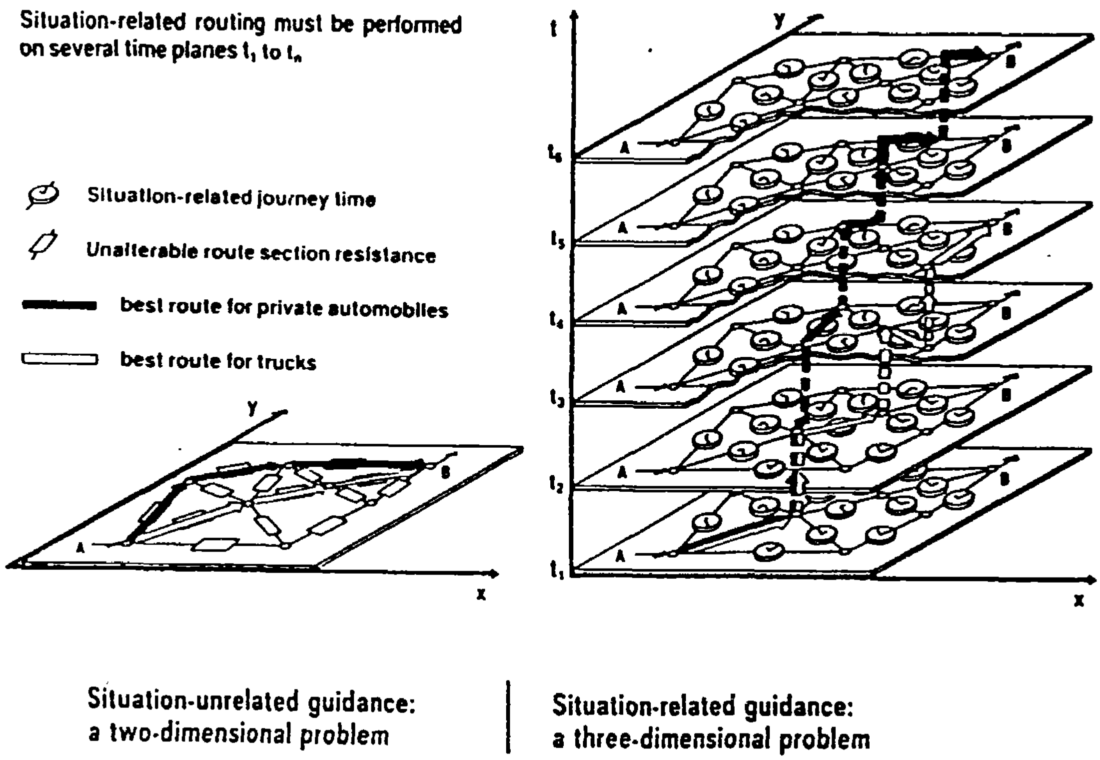

Figure 2.4

(Source: Reference 61)

advice is therefore provided at each decision point on the journey which is up-to-date and takes account of real-time variations in traffic congestion.

Route guidance systems have been a topic of research and development in several countries for over twenty years. Some of the earliest work was carried out in the U.S. in the late 1960s, with the investigation and development of a prototype Electronic Route Guidance System (ERGS) [47, 48]. The system concept was investigated by several organizations including General Motors [49] and Philco-Ford [50], under contract to the Office of Research and Development of the Bureau of Public Roads.

The ERGS concept was based around two-way communication between vehicles and a roadside beacon network infrastructure via in-pavement inductive loops and vehicle-mounted antennas. An in-vehicle console with thumbwheel switches permitted the driver to enter a selected destination code. The code was transmitted when triggered by an antenna as the vehicle approached key intersections. The roadside unit immediately analyzed routing to the destination and transmitted instructions for display on an in-vehicle panel.

In the ultimate system concept, ERGS was envisioned with each roadside beacon connected to a central computer, monitoring feedback on traffic conditions from the loop antennas to update a network database. The ERGS project was terminated in 1970, due to the high projected costs of the roadside infrastructure.

Japanese investigations into short-range externally-linked route guidance with two-way communications have been in progress since the early 1970s. The Comprehensive Automobile Traffic Control System (CACS) project [51, 52, 53], sponsored by the Japanese Ministry of International Trade and Industry (MITI), began in 1973 and ran for a six-year period.

The prototype CACS system demonstrated in Tokyo utilized inductive loop antennas for two-way communications between the vehicle and the roadside. As an equipped vehicle approached a CACS intersection, the vehicle type, an identification number and its coded destination (entered via an in-vehicle unit) were transmitted from the vehicle to the roadside. Routing and driving information were sent in the opposite direction. The roadside equipment was connected to a communications control center which processed travel time information derived from vehicles to continuously update a network condition database. Routing information updates were sent periodically from the control center to the roadside equipment.

The CACS project was completed in 1979, at which time the results of the project were given to a number of organizations concerned with traffic management. In order to carry out further development, building on CACS, the JSK Foundation [54] was established under the direction of the MITI. JSK involves 27 Japanese manufacturers of electronic equipment and motor vehicles.

In 1985, JSK organized a trial of an updated route guidance system in Tsukuba [55] to test out the most recent technologies. The system tested utilized overhead antennas, and the travel time between equipped intersections was computed by the in-vehicle unit. Full results of the evaluation have not been publicly released.

Other Japanese organizations are also active in the field of externally-linked route guidance. These include the Public Works Research Institute (PWRI) of the Japanese Ministry of Construction (MOC) and the Highway Industry Development Organization (HIDO) [56]. HIDO is a consortium of vehicle and electronics manufacturers. A study of externally-linked route guidance involving PWRI and HIDO members started in August 1986 [57] entitled RACS (Road-Automotive Communications System).

RACS involves further investigations of inductive beacon systems, together with experiments on microwave beacons. Trials conducted in 1987 utilizing inductive beacons and a prototype in-vehicle unit with dead reckoning between beacons, were of limited value in that only one-way communication was used. The advantage of the microwave approach over the earlier inductive systems lies in its high data transmission rate, which allows significant quantities of information to be passed between roadside beacons and vehicles. Further trials are planned which will incorporate two-way communications and will utilize the more recent microwave-based technology.

European investigations into short-range externally-linked route guidance have been principally carried out in West Germany. A number of West German manufacturers worked on developing both onboard navigation systems and externally-linked route guidance in the late 1970s and early 1980s. Route guidance systems of particular interest developed around this time were ALI and AUTO-SCOUT.

The ALI system (Autofahrer Leit und Informationssystem) [58, 59] was developed by Blaupunkt. Like ERGS and CACS, it utilized inductive loops for vehicle-roadside communication. It was designed principally for use on the German autobahn network. In the ALI system, the motorist keys in his destination as a seven digit figure using a small keypad. As an equipped vehicle approaches a freeway intersection, the destination code is transmitted via the inductive loop antenna to a roadside unit, which returns routing advice based on current traffic conditions.

Network conditions are monitored in ALI using the inductive loops and roadside units, which act as traffic volume counters over the freeway sections. This information is transmitted every five minutes to a central control computer, which calculates the current traffic situation and forecasts future flows on the various highway sections from the incoming data. Appropriate routing advice is then sent back to the roadside units, ready for transmission to equipped vehicles.

The AUTO-SCOUT system [60] was developed by Siemens and utilized infra-red technology for roadside-vehicle communications. AUTO-SCOUT was designed to include a more sparse network of beacons, with only around 20 percent of all significant intersections equipped. At each beacon, travel times on previous highway sections are transmitted from the in-vehicle unit to the roadside equipment, and then to the central computer. A description of the local road network and the recommended route to the next beacon are then transmitted back to the vehicle. Vehicle location and route-following between the beacons is achieved by a navigational computer utilizing dead reckoning.

More recently, the ALI-SCOUT system [61] has been developed in a cooperative effort by Bosch/Blaupunkt and Siemens, using experience gained from ALI and AUTO-SCOUT. ALI-SCOUT (Figure 2.5) is an infra-red based system which utilizes a roadside infrastructure consisting of post-mounted infra-red transmitter/receivers. It has many similar features to AUTO-SCOUT, including an in-vehicle dead reckoning unit for navigation between beacons. The basis for providing guidance information is travel time data, which are received from equipped vehicles at each beacon. This is analyzed in a central computer, which updates map information giving relative impedances of alternative routes held by the roadside equipment.

A large field trial of the ALI-SCOUT system known as LISB began in Berlin in June, 1989. Infrared beacons were installed at 250 intersections and at 10 additional freeway locations. The field trials were designed to permit an evaluation of system performance, driver acceptance and user benefit, using a fleet of 700 specially equipped vehicles [62].

In Britain, the Transport and Road Research Laboratory (TRRL) has taken an active interest in externally-linked route guidance systems since the early 1980s, when TRRL undertook a study [63] in association with Plessey Controls. Demonstration systems [64] utilizing inductive loop technology were set up on the TRRL test track and were used to show the practical feasibility of externally-linked route guidance.

This work formed the initial basis of proposals for a London AUTOGUIDE system [65, 66]. AUTOGUIDE will use a network of strategically located roadside beacons, a central computer and two-way communications with in-vehicle transceiver units, to provide drivers with real-time information on the best route to take between any two points. The elements of the AUTOGUIDE proposal are shown in Figure 2.6.

During the initial investigation of AUTOGUIDE [67], a choice was made between inductive loops or infra-red beacons for the roadside equipment to receive and transmit information. The main determining factors here were data transfer rate, cost and reliability. Post-mounted infra-red beacon systems are cheaper to install than loops and allow more information to be handled, with a potential data transfer rate of 500 Kbaud. A decision was made that further development and demonstration should concentrate on the infra-red approach, with a final commitment dependent on the results of field trials.

Work was subsequently carried out on the implementation of an AUTOGUIDE demonstration scheme in London [68]. The demonstration started in 1988 and utilized five beacons, sited along a corridor between Westminster and London's Heathrow Airport. In the demonstration beacons were not connected to a central computer, since the number of equipped vehicles and beacons was insufficient to collect detailed traffic data. Nevertheless, the demonstration was successful in verifying the infrared road-vehicle communications link and the format of the in-vehicle display unit.

The successful completion of the AUTOGUIDE demonstration led to the distribution by the U.K. government of a bid document for installation of an AUTOGUIDE pilot

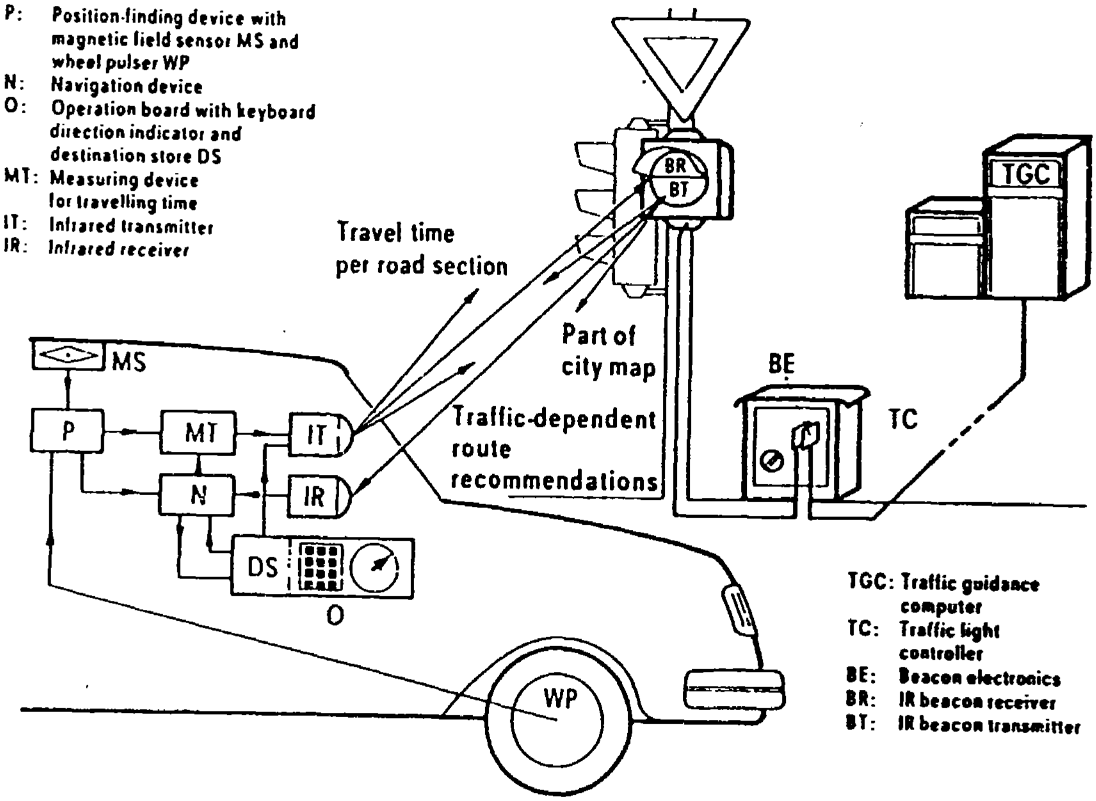

Figure 2.5 The ALI-SCOUT system

(Source: Reference 61)

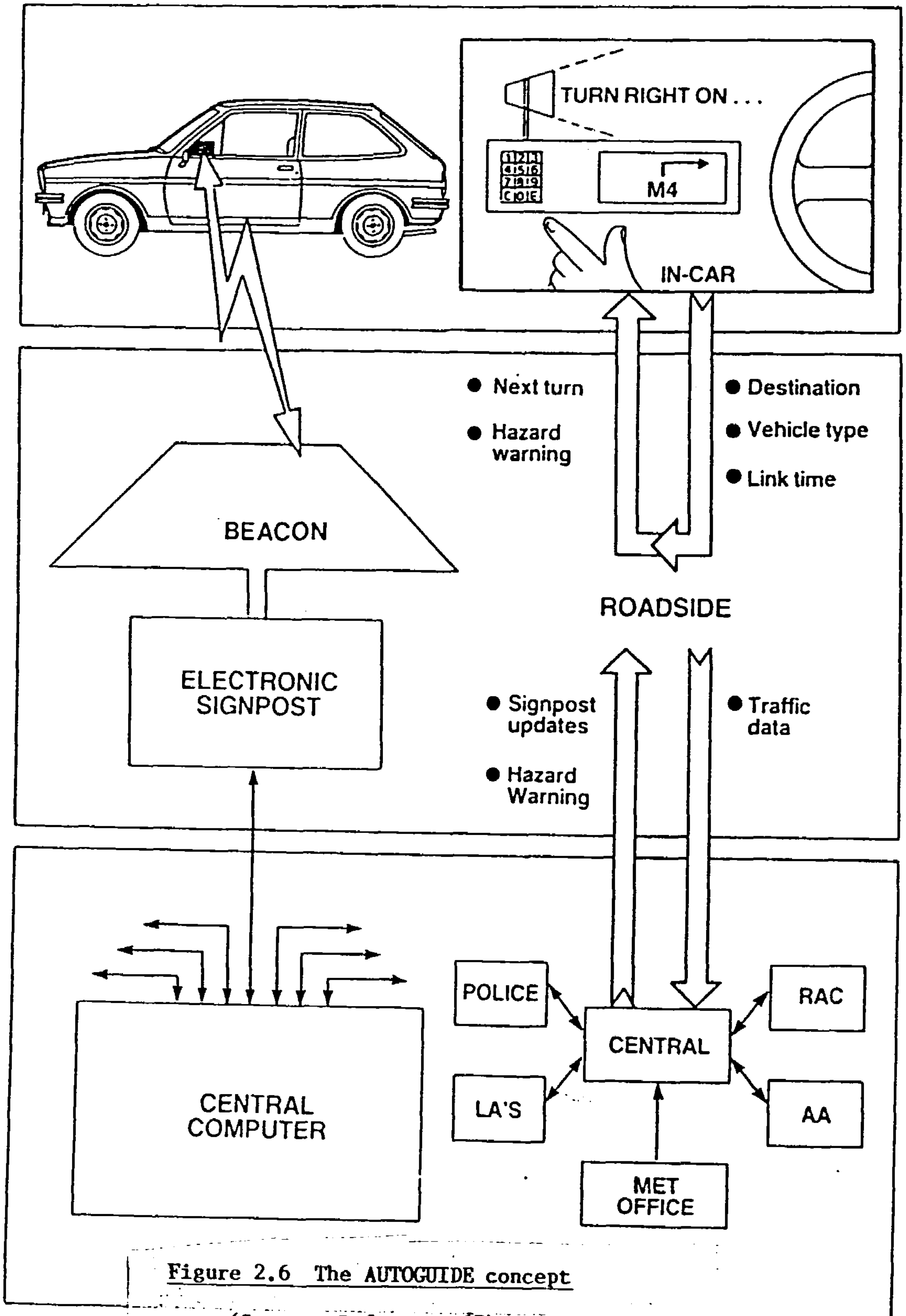

Figure 2.6 The AUTOGUIDE concept

(Source: Reference 67)

system. This would initially operate within the area encircled by the London beltway, before being extended to other parts of the country. GEC was selected by the U.K. government as the contractor for the AUTOGUIDE implementation. At the time of writing, however, negotiations between GEC and the U.K. government have yet to achieve agreement on the system licensing details. It is understood that one of the causes of the delay is local councils in the London area, which have expressed concern over the ways in which AUTOGUIDE will select and recommend routes in their areas of jurisdiction.

2.6 Automatic vehicle identification

Automatic vehicle identification (AVI) is the term used for techniques which uniquely identify vehicles as they pass specific points on the highway, without requiring any action by the driver or an observer. AVI systems [69] essentially comprise three functional elements: a vehicle-mounted transponder or tag; a roadside reader unit, with its associated antennas; and a computer system for the processing and storage of data. At the simplest level, information which identifies the vehicle is encoded onto the transponder. This normally consists of a unique identification number, but can also include other coded data. As the vehicle passes the reader site, the transponder is triggered to send the coded data via a receiving antenna to the roadside reader unit. Here, the data are checked for integrity before being transmitted to the computer system for processing and storage.

Two-way communication is also possible with some AVI systems. Here, data flow occurs in both directions, with coded messages being transmitted between the reader unit and vehicle-mounted transponders. More sophisticated technology is needed for this type of system, with additional capabilities required in both the roadside and vehicle-based equipment.

AVI can potentially contribute to relief of urban traffic congestion in a number of ways through its vehicle-roadside communications link. One of its potential applications lies in providing real-time travel speed information, which can then be utilized as an input to traffic information systems such as HAR, RDS or AMTICS. At the simplest level, a coded vehicle identification number can be passed from the vehicle to the roadside each time a reader unit is passed. This identification data can be processed by a central computer to obtain journey times between the various distributed reader units in an AVI network, giving an indication of traffic conditions between these points.

AVI systems with full two-way vehicle-roadside communication allow messages to be passed back from the roadside reader station to the vehicle. Vehicles could potentially be warned of congested areas, accidents or adverse weather conditions, enabling drivers to take alternative routes. The network condition information forming the basis of these messages would be derived by the central computer from journey time information computed from the AVI data passed from vehicles to the roadside.

A significant project currently running in the field of AVI is the Heavy Vehicle Electronic License Plate (HELP) program. The $19 million HELP program is funded and directed by a group of 14 states, as well as the Port Authority of New York and New Jersey, the federal government and various motor carrier organizations. The aim of the program is to develop an integrated truck traffic information and management system combining AVI, weigh-in-motion and automatic vehicle classification technologies with a networked data communications and processing system, comprising roadside stations linked to regional and central computers [70, 71, 72].

Automatic vehicle identification systems can be used as a tool for implementing traffic restraint policies aimed at reducing congestion levels. Road pricing is one approach to traffic restraint for which AVI is an ideal implementation tool. The theory of road pricing [73] is that road users should pay for their use of road space according to how much they are contributing to congestion. It therefore depends upon charging vehicles for being in a particular place at a particular time. AVI systems linked to a computer network can be used to set up toll sites on the highway network using AVI readers. Road user charges can be varied by time of day and location, according to congestion levels. Vehicles equipped with AVI transponders debit an account each time they cross a toll site, and are subsequently billed for their road usage.

AVI has been demonstrated for road pricing in Hong Kong on a trial basis, [74, 75] and has been shown to be technically feasible (Figure 2.7). However, there are significant issues of public acceptability concerned with using AVI for this purpose which need to be considered. First, traffic restraint policies in themselves tend to be controversial and unpopular with a significant proportion of the population. Second, use of AVI for road pricing requires that all vehicles which enter the congested area are fitted with an AVI transponder or "electronic license plate." This mandatory fitting of electronic license plates raises privacy objections which contribute to the difficulties of implementing AVI systems for this particular application.

Finally, AVI systems may alleviate congestion where they are utilized for automated toll collection. AVI-based automatic toll collection facilities have been under consideration for several years, with experiments carried out by the New York and New Jersey Port Authority, Caltrans [76] and the Golden Gate Bridge Authority. An operational system is currently being implemented on the Dulles Toll Road in Virginia [77]. In this application, regular users of toll bridges, tunnels or turnpikes opt to have their vehicles fitted with AVI transponders, so that they do not need to stop to hand over cash when driving through the toll plaza. AVI fitted vehicles are automatically identified and the appropriate charges are calculated by a computer system. These are either automatically deducted from a pre-paid account or users can be billed at regular intervals. Use of this type of system should increase the throughput of toll facilities, reducing the level of congestion at the toll plaza and on the approach roads.

A number of approaches to automatic vehicle identification have been developed since the first investigations of AVI were carried out in the 1960s. Recent advances in vehicle detection and data processing techniques have made the application of AVI systems both technically and economically feasible. AVI system can be divided into four main categories as described in the following paragraphs.

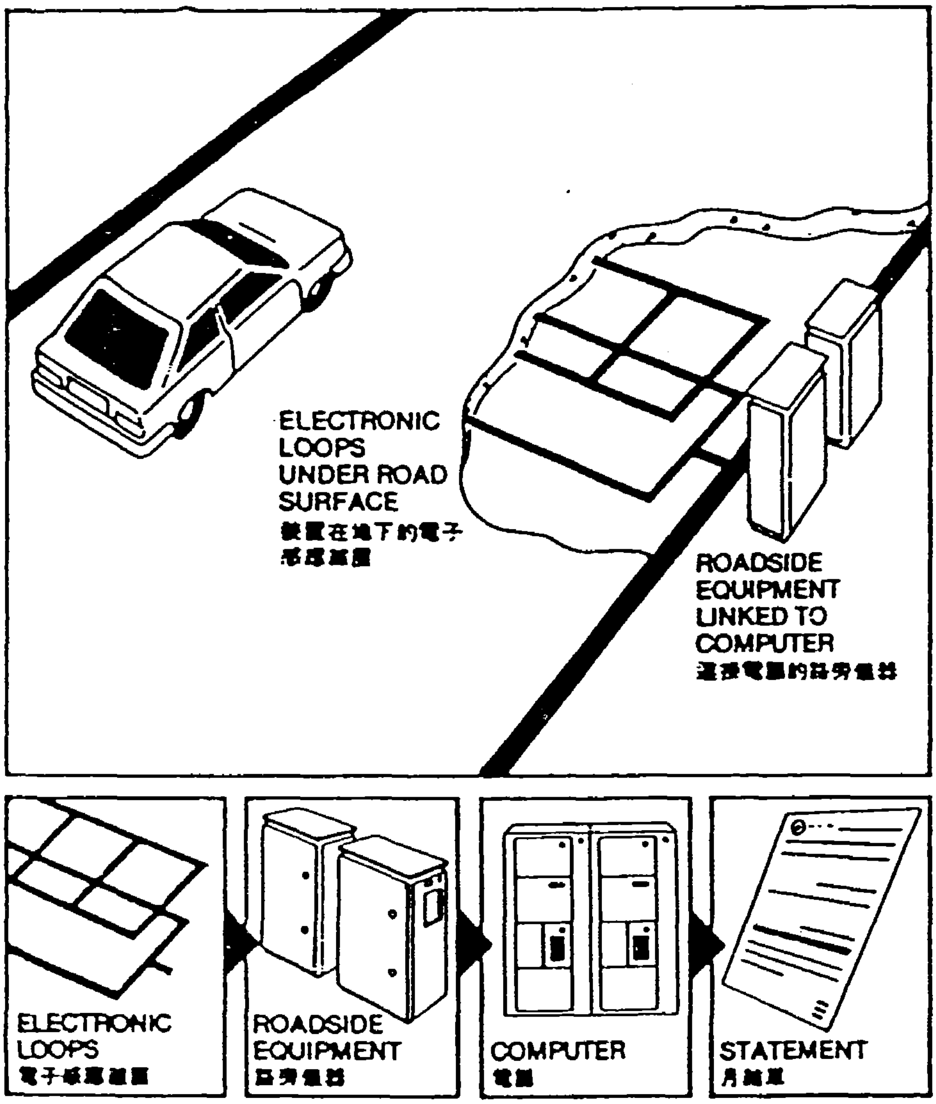

Figure 2.7 The Hong Kong electronic road pricing system

(Source: Reference 74)

Optical systems formed the basis of the earliest AVI technologies developed in the 1960s in the U.S. and Europe. However, optical systems require clear visibility, performance being seriously degraded by snow, rain, ice, fog or dirt. They are also sensitive to reader/tag misalignment, focusing problems and depth of field limitations, though improvements in performance have been achieved in recent years. A recent project undertaken at the University of Arkansas carried out investigations into bar-code optical AVI systems. The results suggest that, even with modern technology, the level of reliability of optical AVI is too low for many highway transportation applications.

Infrared systems were tried during the 1970s as a substitute for the earlier optical approaches, but were found to share many of the problems of the earlier optical systems, being similarly sensitive to environmental conditions. AVI applications usually require very high read reliability levels and the fundamental nature of these problems is such that both optical and infra-red approaches have been largely abandoned by AVI manufacturers.

Inductive loop AVI systems use conventional traffic detection and counting loops in the highway pavement to detect signals from transponders mounted on the underside of vehicles. These approaches can be divided into active, semi-active and passive systems, according to the source of power used by the vehicle-mounted transponder.

Radio frequency (RF) and microwave systems generally utilize roadside mounted or in-pavement antennas, transmitting or receiving on a wide range of frequencies in the kHz, MHz and GHz ranges. These systems can also be divided into active, semi-active and passive approaches.

One advantage of microwave systems is that they can transmit data at much higher rates than inductive loop systems, as they operate at higher frequencies. However, a potentially serious problem associated with microwave passive systems concerns the power levels which must be transmitted in order to energize the vehicle-mounted tags. In many countries these may violate limitations on accepted safe operating levels for microwave systems. Semi-active systems offer a compromise, using a sealed unit transponder with an internal battery. These allow radiated power levels to be greatly reduced, while providing for a transponder design life of several years.

Surface acoustic wave (SAW) technology is the basis of another AVI approach [78, 79]. A SAW tag consists of two elements, an antenna and lithium niobate SAW chip that serves as a multi-tapped electronic delay line. The SAW chip receives an interrogating signal through the attached antenna, stores it long enough to allow other reflected environmental interference to die out and then returns a unique phase-encoded signal. The key operating characteristic of the SAW chip is the ability to convert the electromagnetic wave into a surface acoustic wave. SAW tags overcome concerns over high microwave power levels but are limited to purely fixed-code applications.

2.7 Summary

In summary, a range of systems is being developed and demonstrated which can provide drivers with information on highway conditions and route availability. Traveler information systems have potential to assist motorists in the three key activities of route planning, route following and trip chain sequencing. In particular, electronic route planning systems offer pre-trip advice, potentially reducing the proven inefficiencies in driver route selection. New traffic information broadcasting techniques offer greatly increased coverage and selectivity, to alert drivers to ever-changing traffic situations. On-board navigation systems help drivers find and follow a preferred route, while externally-linked route guidance seeks to combine route choice with real-time response to congestion within a truly dynamic system.

3. ADVANCED TRAFFIC MANAGEMENT SYSTEMS

3.1 Introduction

Control of traffic in time as well as space adds a fourth dimension to traditional highway engineering solutions to the congestion problem. The coordination of road space and road time on a particular ramp or intersection can be extended to wide-area schemes capable of securing major traffic benefits at relatively modest cost. The proven benefits of traffic management include freer traffic flows, shorter journey times, substantial fuel savings, and generally reduced congestion. Because the benefits can be great, the use of these techniques is already widespread in the U.S. and overseas [80, 81, 82].

Operational objectives of advanced traffic management systems (ATMS) include making the best use of existing highway network capacity and cutting journey times, without creating adverse environmental effects [83]. By reducing congestion and delay, some systems have been utilized to produce fuel savings or to reduce traffic noise and vehicle emissions. Linked with other systems, urban traffic control (UTC) can provide the basis for an expanded control philosophy incorporating features such as variable message signs, congestion monitoring, emergency vehicle priority and other intervention strategies. In the longer term, current techniques could be extended into areas such as expert system traffic control, and interaction with ATIS technologies such as the route guidance techniques described in the previous chapter [84, 85].

Traffic control systems can also be used to influence the pattern of route choice in pursuit of policy objectives such as protection of residential environments, increasing safety, assisting pedestrians or giving priority to transit vehicles. As well as being reduced, congestion can be re-distributed between geographic areas or between categories of the highway system to arrange for queuing to take place in areas where it can best be accommodated. Warnings can be directed from traffic control centers through variable message signs or in-vehicle information systems to help prevent secondary accidents and to direct vehicles away from congested areas.

This chapter considers recent and ongoing developments in the field of ATMS. It includes fixed-time and traffic-responsive urban traffic control (UTC) strategies; incident detection techniques; freeway and corridor control systems; and future possibilities for interactive control, combining these techniques with those described in the previous chapter.

3.2 Traffic signalization

Traffic signals on urban highways allow vehicle movements to be controlled through time and space segregation, speed control and advisory messages. Signal equipment and control techniques have evolved to deal with a wide range of highway situations and traffic demands. This section considers how available techniques might be better utilized, and goes on to examine some new and upcoming approaches with greater potential.

Coordination between adjacent traffic signals on arterials, ramps or grids requires some form of plan or strategy to integrate individual signal timings on a wide-area basis. Both fixed-time and traffic-responsive strategies of control have been developed and are now applied in urban areas in many parts of the world. Fixed time coordination is commonly utilized in most cities, while traffic responsive techniques are becoming more widespread in some other countries [86, 87].

Although advanced technologies may have much to offer in the field of traffic control, it is also worth considering what could be accomplished by better utilization of existing approaches. Techniques already exist for the determination of optimal signal timings at isolated intersections and in fixed-time coordinated networks. The hierarchy of signal timing systems can be divided into the following categories, each of which is discussed in subsequent paragraphs:

* isolated intersection control;
* fixed-time coordination;
* partially-adaptive coordination;
* fully-adaptive coordination; and
* fourth generation systems.

Isolated intersection control systems may be operated fixed-time, semi-actuated or with full vehicle-actuation. Whichever strategy is used, there is often scope for improvements in signal timings to reduce delays. The very simplest methods derive green splits manually, in proportion to expected traffic demand. More complex methods calculate signal timings according to a predetermined performance measure and involve some form of computer optimization [88, 89, 90, 91, 92].

SOAP84 is a computer program developed for the FHWA and used for optimizing isolated intersection settings. The model calculates optimum cycle time and green splits based on a modified Webster's method [93, 94].

Current developments in isolated intersection control are looking toward advanced control strategies to replace current methods of vehicle actuation. MOVA (Modernized Optimized Vehicle Actuation) works on a principle of approach occupancy, and trades off stopping approaching vehicles against holding already-stopped vehicles for a few more seconds. Two sets of loops are used on each approach at distances of 130 feet and 330 feet from the stopline [95]. The LHOVA algorithm adopts a similar approach [96, 97].

Fixed-time coordination is another area where much could be achieved through the wider use of established techniques. In 1982 it was estimated that there were some 130,000 sets of traffic signals in the U.S. which formed some part of coordinated systems [98]. Cimento [99] described progress made during the 1960s and 70s in bringing these systems under electronic computerized control (Figure 3.1).

The concept of coordination is to control the durations and offsets of green periods at adjacent sets of signals along an arterial or within a network. To maintain coordination from cycle to cycle, each intersection must operate with a common cycle time, or sometimes half the basic cycle. The green periods at each intersection are timed in relation to each other by specifying an offset for each set of signals, based on the average journey time along each link. The offset is the starting time of a specified phase, measured against a common time base of one cycle duration.

Coordinated signal timings for arterials were first produced manually using time and distance diagrams. In many areas, signal plans are calculated using computerized versions of the time and distance concept, typically providing maximum bandwidth "green wave" progression on limited numbers of arterials. Examples of computer programs for maximizing bandwidth and progression along arterials include MAXBAND [100] and PASSERII-84 [101].

For grid networks, one of the first, national initiatives to develop efficient fixed time coordinated traffic signal timings was the SIGOP program [102], produced in 1966 for the Bureau of Public Roads. The SIGOP optimization routine utilizes an algorithm which depends on two variables: ideal offset, calculated from speed, link length, and queue discharge time; and link weighing, which can either be specified as input data or calculated by SIGOP in proportion to the competing approach volume demands.

More recently, a different approach has been utilized for coordinating fixed-time signals, based on network optimization. The TRANSYT (Traffic Network Study Tool) program models traffic behavior, carries out an optimization process, and calculates the best signal settings for the network. The program also provides extensive information about the performance of the network including estimated delays, numbers of stops, journey speeds and fuel consumption. TRANSYT has been extensively documented and only and a few references are quoted here [103, 104].

TRANSYT models traffic behavior using histograms to represent the arrival patterns of traffic. The histograms are called cyclic flow profiles [105] because they represent the average rate of traffic flow during one signal cycle (Figure 3.2). The signal optimizer searches systematically for a good fixed-time plan by minimizing a performance index such as the weighted sum of delays and stops on all links of the network. Specific links can be further weighted to give priority to HOVs or to guarantee green waves along arterials. Otherwise, TRANSYT seeks a global optimum, trading-off the needs of arterials, side-roads and grid sections of network to calculate efficient signal settings for the area as a whole.

One of the earliest evaluations of TRANSYT was performed in Glasgow, Scotland in 1968 [106]. TRANSYT was still in its developmental stages, and was compared with existing uncoordinated vehicle actuation. The results of the Glasgow trial showed an average 16 percent reduction in vehicle delays using the TRANSYT

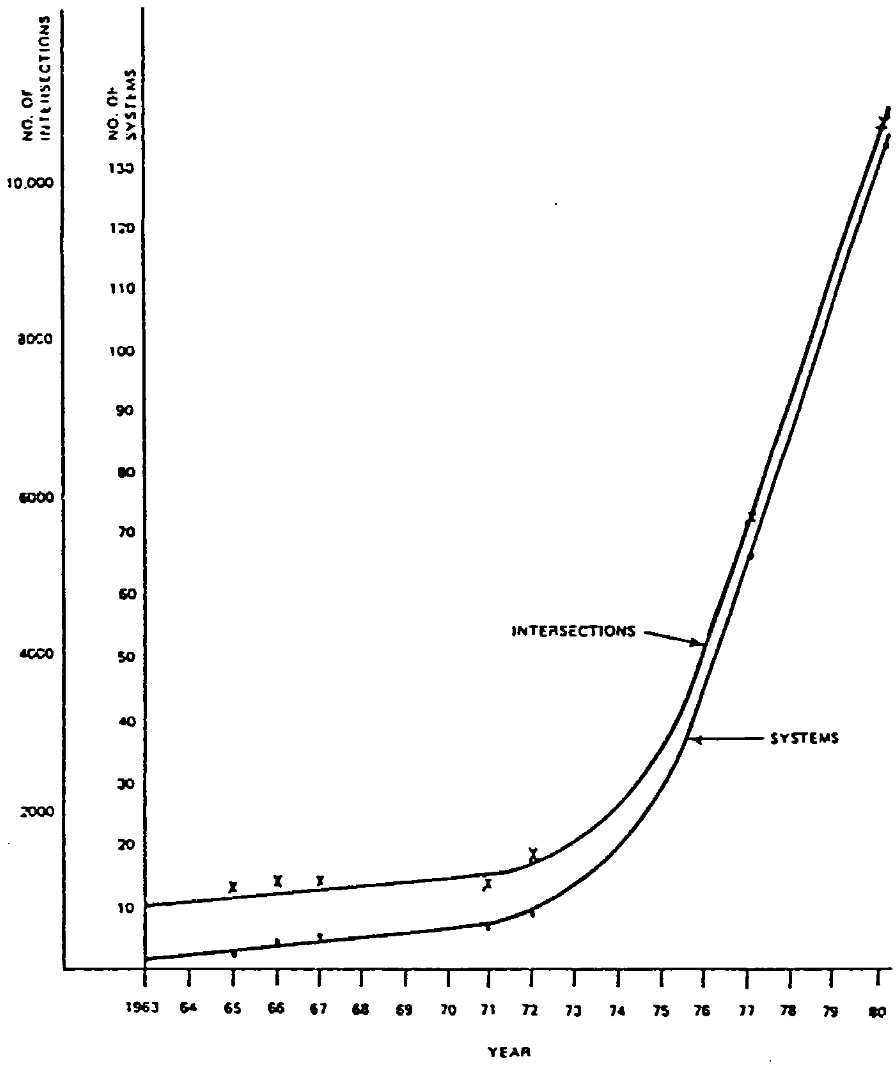

Figure 3.1 Number of computerized traffic control systems and controlled intersections in the US

(Source: Reference 99)

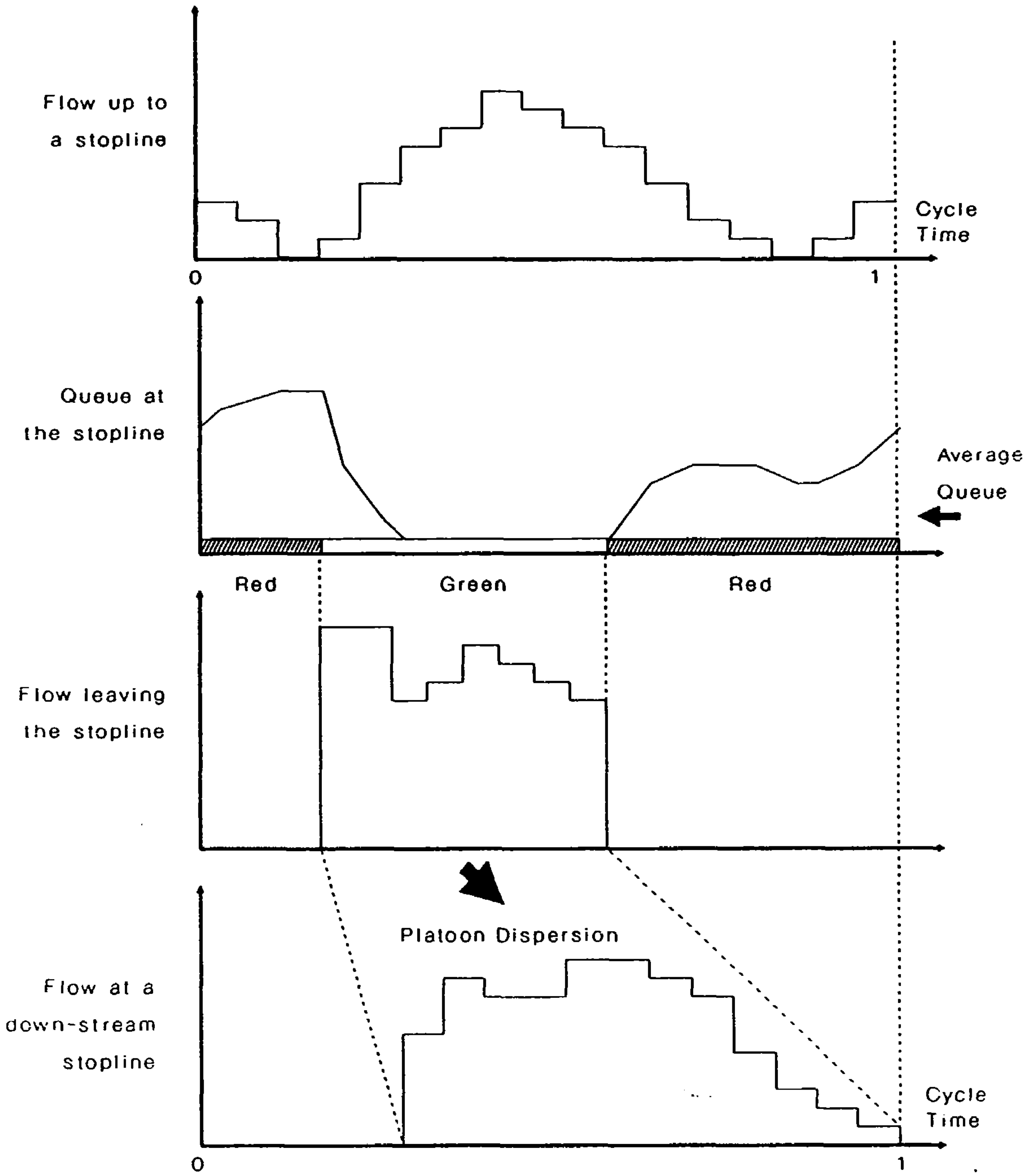

Figure 3.2 Cyclic flow profile in the TRANSYT model
(Source: Reference 104)

method, compared with the existing system. The maximum benefits were apparent during the morning and evening peak periods.

The current version of TRANSYT-7F was developed by the University of Florida Transportation Research Center, and evaluated in the NSTOP project [107, 108]. Since 1981, TRANSYT-7F has gone through five releases. Initially, a fuel consumption model was added to allow for optimization of energy usage. A Platoon Progression Diagram (PPD) capability was subsequently included, showing traffic densities at all points in time along links in a time-space diagram format. Release 5 now provides four new capabilities:

1. a gap acceptance model for permitted, opposed movements;

2. explicit treatment of "sneakers," who turn left at the end of a permitted phase;

3. explicit treatment of stop sign control; and

4. modeling of shared left and through lanes.

TRANSYT-7F has been widely evaluated and applied, in programs such as FETSIM [109, 110, 111, 112].

In Europe, also, enhancements to the TRANSYT program have continued, with two recent versions providing increases in capability. TRANSYT-8 included a fuel consumption model, explicit treatment of yield control, provision for modeling opposed turning movements, and inspection of a range of cycle lengths. More importantly, however, it incorporates a capacity-sensitive component in the performance index, limiting queue formation on short links by "gating" or metering traffic in the vicinity of critical intersections.

The recent TRANSYT-9 incorporates three further updates. These are:

1. an interactive editing program for creating and modifying data input files;

2. a routine allowing users to examine the effects of different phase sequences; and

3. an interactive program for demonstrating queue and performance index graphs for individual links over one complete cycle.

The benefits offered by any new fixed-time signal plan will depreciate over time as traffic conditions change and the plan becomes less appropriate. Experience shows that signal plans degrade by about 3 percent per year, so that the initial benefit can be lost within five years. Actual rates of ageing may vary significantly about this mean and will tend to be more acute in grids than along arterials [113].

The aging process arises from:

* changes in traffic demands over the whole network;

* changes in traffic flows on specific links due to re-routing or demand shifts; or

* physical or regulatory alterations to the street network.

This aging process implies that retiming programs such as FETSIM need to be a permanent feature with all fixed-time signal coordination schemes. In practice, updates occur infrequently because of the time and costs involved, even though such actions would be highly cost-effective. It is to avoid these problems that traffic-responsive coordination systems have been developed. These systems are described below.

Partially-adaptive coordination approaches monitor traffic conditions in a network using some form of detection, and react to the information received by implementing appropriate signal settings. In other words, systems of this kind adapt themselves to traffic patterns and respond to traffic demands as they occur.

A good fixed-time system will typically require four to eight changes of plan during a normal weekday. In some cities, controller equipment permits only a single plan to be operated all day, while other systems allow only separate plans for morning peak, inter-peak and evening peak [114]. In more advanced systems, libraries of eight or ten alternative plans are normally prepared and switched-in as required. Sometimes plan changes are carried out manually based on visual surveillance of traffic conditions using closed circuit television cameras (CCTV). However, the most common method is to change plans at particular times each day, determined historically in the light of expected traffic conditions.

The simplest form of traffic-adaptive system involves automated plan selection. In this method of control, the information received from on-street detectors at critical intersections is used to select the most appropriate signal plan from a pre-determined library. Although this method provides a degree of self-adjustment to prevailing traffic conditions, it still requires the time-consuming preparation of signal plans off-line. Evaluations also suggest there is no convincing evidence that systems which select fixed-time plans on the basis of flows and congestion measurements perform any better than the simpler procedure of changing plans by time of day [106, 115].

The major U.S. initiative in this area was undertaken within the Urban Traffic Control System (UTCS) project initiated by the FHWA. The first generation UTCS control system began operating in 1972 at a test facility in Washington, D.C. In this system, detector data were used automatically on-line to select appropriate cycles, splits and offsets.

The first generation software used prestored timing plans developed off-line, based on previously generated traffic data. Plan selection options included manual, time-of-day and automated plan selection based on recent volume and occupancy data. The results of the UTCS-1 test in Washington, D.C. showed improvements over previous control systems. Within the test, the traffic responsive strategy of automated plan selection showed small, but generally significant benefits over alternatives such as time-of-day selection. A further test in New Orleans showed larger benefits overall for UTCS-1 relative to previous equipment. However, in this case time-of-day was marginally ahead of automated plan selection.

At the present time, generation 1.5 UTC systems represent a step toward traffic-responsive approaches, potentially replacing wholly fixed-time operation. Work on the development and implementation of generation 1.5 concepts can be seen in the ATSAC (Automatic Traffic Signal and Control) system implemented in Los Angeles [116]. In the ATSAC system, enhanced UTC equipment utilizes loop detectors for flow monitoring to identify when signal plan changes are required. Off-line plan development is also partially automated, based on data from the on-street detectors.

Development of a second generation UTCS strategy was also undertaken. This approach represented a real-time, on-line system that computes and implements signal timing plans based on surveillance data and predicted changes. UTCS-2 retained many features of the first generation system. However, UTCS-2 results showed network-wide degradation in performance in every instance relative to the base case three-dial system. Increases in delay ranged from 1.1 percent to 9.3 percent with the worst results occurring during the evening peak period. Slight improvements (2 percent) were measured on the arterial portion of the network, but it is unclear whether these gains were statistically significant.

The lack of success of the earlier second generation vehicle-responsive systems led to investigation of the reasons for failure. Some of the problems of this adaptive systems approach are believed to be [117]:

* **Frequent plan changing.** Most of the second generation methods of control required that new plans be calculated on-line and implemented as soon as possible. Even the best methods of plan-changing cause significant transition delay and so a new plan must operate for more than 10 minutes to achieve an overall benefit.

* **Inadequate prediction.** From the above it is seen that a prediction for several minutes into the future is necessary. Random variations in traffic make this prediction very difficult. Historical data may be needed to help identify trends.

* **Slow response.** When unexpected events occur, the response is delayed by the historical element of prediction and the need for a new plan.

* **Effects of poor decisions.** Unexpected events or faulty detector data may cause poor plans to be implemented which cannot be corrected until the next plan update.

The SCATS system, developed and initially implemented in Sydney, Australia, is said to overcome the problems identified with early second-generation systems [118]. SCATS combines several features of UTCS-1 and 2, using background traffic control plans selected in response to traffic demand. Signal timings within these plans are determined according to traffic conditions at critical intersections which control coordination within small subsystems.

The subsystems vary in size from one to ten intersections and, as far as possible, are chosen to be traffic entities which can run without relation to each other. As traffic demands increase, the subsystems coordinate with adjacent subsystems to form larger groupings. This 'marriage' and 'divorce' of subsystems is calculated using simple empirical rules based on traffic flows and intersection spacings.

Each subsystem requires a substantial database, including minimum, maximum and geometrically optimum cycle lengths, phase split maxima and offset times. Background plans are stored in the database for each subsystem. Cycle length and the appropriate background plan are selected independently to meet the traffic demand, using data from stop line detectors at critical intersections. Empirical relationships are used to decide whether the current cycle and plan should remain or be changed.

At peak periods, SCATS determines subsystem cycle lengths according to traffic demands at critical intersections, using Webster's method. Offsets are pre-calculated to suit the busier direction of travel. Progression is not guaranteed in the less busy direction at peak times [119]. During off-peak periods, SCATS selects the minimum of two or three pre-calculated cycle times giving good two-way time-distance progression [120].

Fully-adaptive coordination approaches represent a goal sought by researchers in several countries throughout the 1970s. In the U.S. work on UCTS-3 was designed to create a fully responsive, on-line traffic control system.

UTCS-3 [121] utilized two optimization algorithms: an approach with no fixed cycle times, for under-saturated conditions, and congested intersection control/queue management control for use along congestion paths. In the former approach, signal coordination was accomplished by implementing a coarse simulation of traffic flow, and then systematically adjusting signal settings to minimize a weighted sum of delays and stops. The congestion algorithm aimed to maximize thoroughput and manage queue lengths to avoid blocking adjacent intersections.

Results of a UTCS-3 evaluation in Washington, D.C. showed increases in delay ranging from 3.4 percent to 15.2 percent relative to the base case three-dial system. Overall, the third generation system produced about 10 percent more delay than the previous system utilized in Washington, D.C.

In Europe a coordinated, fully responsive traffic control strategy was developed by the U.K. Transport and Road Research Laboratory (TRRL). The system is called SCOOT, an acronym for Split, Cycle and Offset Optimization Technique. This system was developed in association with three electronics companies - GEC, Plessey and Ferranti, who now market the software. SCOOT reacts automatically to changes in traffic flow, adjusting the cycle time, the splits, and the offsets in accordance with an on-line optimization process.

SCOOT monitors cyclic flow profiles in real time for input to a TRANSYT-type optimization. The vehicle detectors are inductive loops, located well upstream of each intersection, usually close to the preceding signal (Figure 3.3). SCOOT uses this information to recalculate its traffic model predictions every few

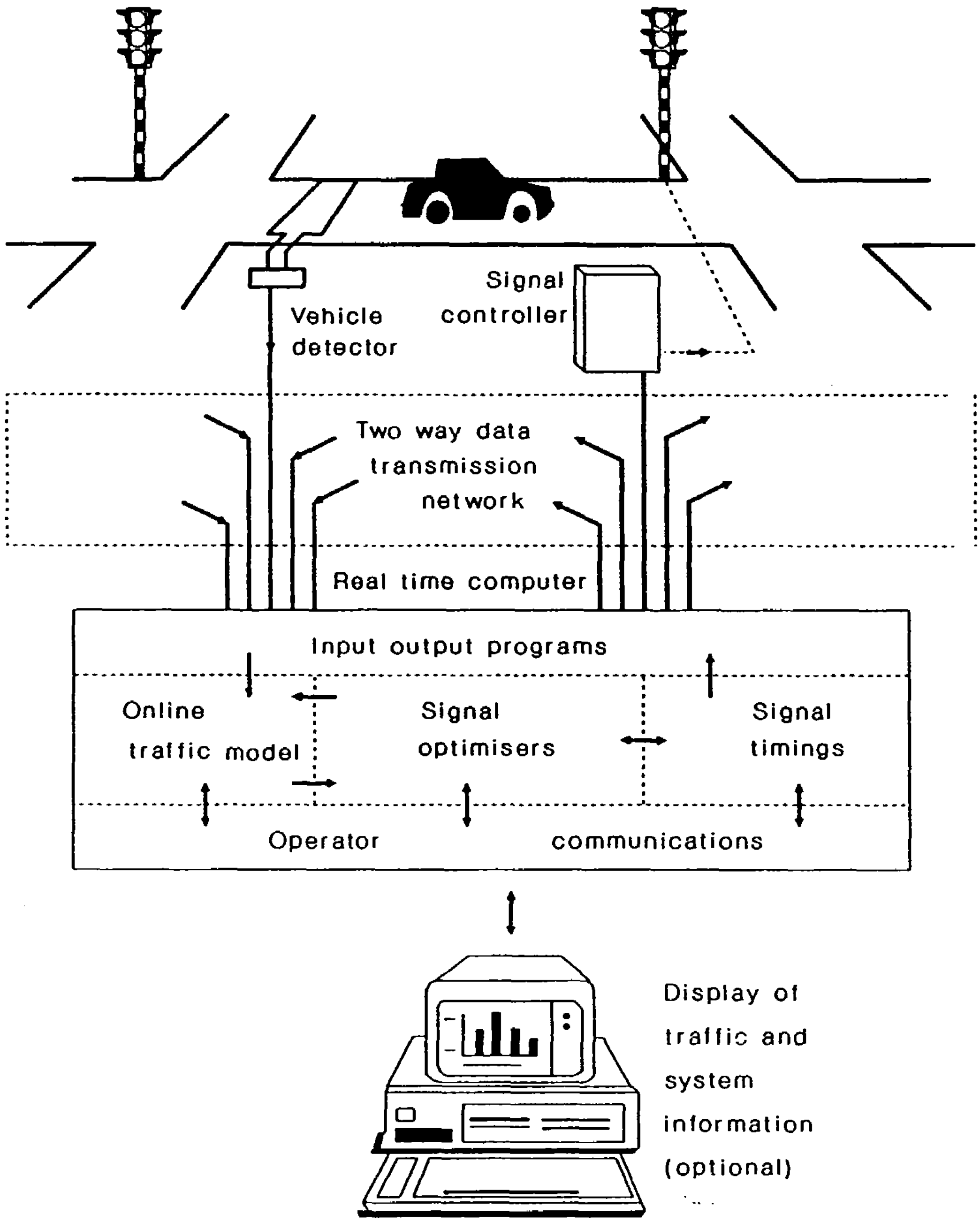

Figure 3.3 The flow of information in a 'SCOOT' UTC system

(Source: Reference 121)

seconds and makes systematic trial alterations to current signal settings, gradually implementing those alterations which the traffic model predicts will be beneficial. The principles of the SCOOT traffic model are illustrated in Figure 3.4.

The first trials of fully adaptive control were carried out in 1975 [121], at the end of an initial research and development phase. These encouraged the U.K. Department of Transport to develop the system for general use. Further research by TRRL led to an improved system which was evaluated in Glasgow during Spring 1979. SCOOT was compared with up-to-date, carefully optimized fixed-time TRANSYT plans. Both in this evaluation, and in subsequent trials in other cities, SCOOT has consistently improved upon fixed-time TRANSYT control by significant margins.

Research suggests that adaptive control is also likely to achieve an extra 3 percent reduction in delay each year, relative to fixed time control, as fixed time plans age and become less appropriate for current traffic flows [113]. Over the four to five years between TRANSYT updates typically occurring in well-maintained systems, this would accumulate to an extra 12 to 15 percent. In many instances, where fixed time plan updates are less frequent, the benefits of a traffic-responsive system could be larger.

Fourth generation systems represent the highest level of signal control complexity considered within this review. Systems such as SCOOT do not represent the end of the line in traffic control strategies, and are in a very real sense already 15-year old technology. Some of the limitations of SCOOT-type approaches which need to be addressed by future fourth generation systems include:

1) The current policy of minimizing transients and allowing only "creeping" plan changes is beneficial in maintaining coordination but mitigates against the objective of fast response when conditions change rapidly, for example due to an incident. A fourth generation system would decide when to kick-in a remedial plan, which the system would then fine-tune using an incremental optimization.

2) While TRANSYT's heuristic optimization technique is normally specified to try both large and small step sizes within the process of seeking a global optimum, incremental changes as well as limitations on processing power inherently restrict the scope of SCOOT to an essentially local optimization. Field evaluation shows that this is not a major problem. However, a fourth generation system should be able to take occasional large steps to radically new plans, subject always to an evaluation of the disruption resulting against the eventual benefit.

3) By monitoring cyclic flow profiles at the beginning of each link, and necessarily smoothing out random fluctuations in traffic flow, SCOOT effectively , for recently past traffic conditions, rather than the upcoming situation. The amount of lag differs in respect of split, offset and cycle. A fourth generation system would contain subsystems for short-term forecasting, based initially on historical data and real-time O-D estimation, and perhaps later on feedback from externally-linked route guidance systems.

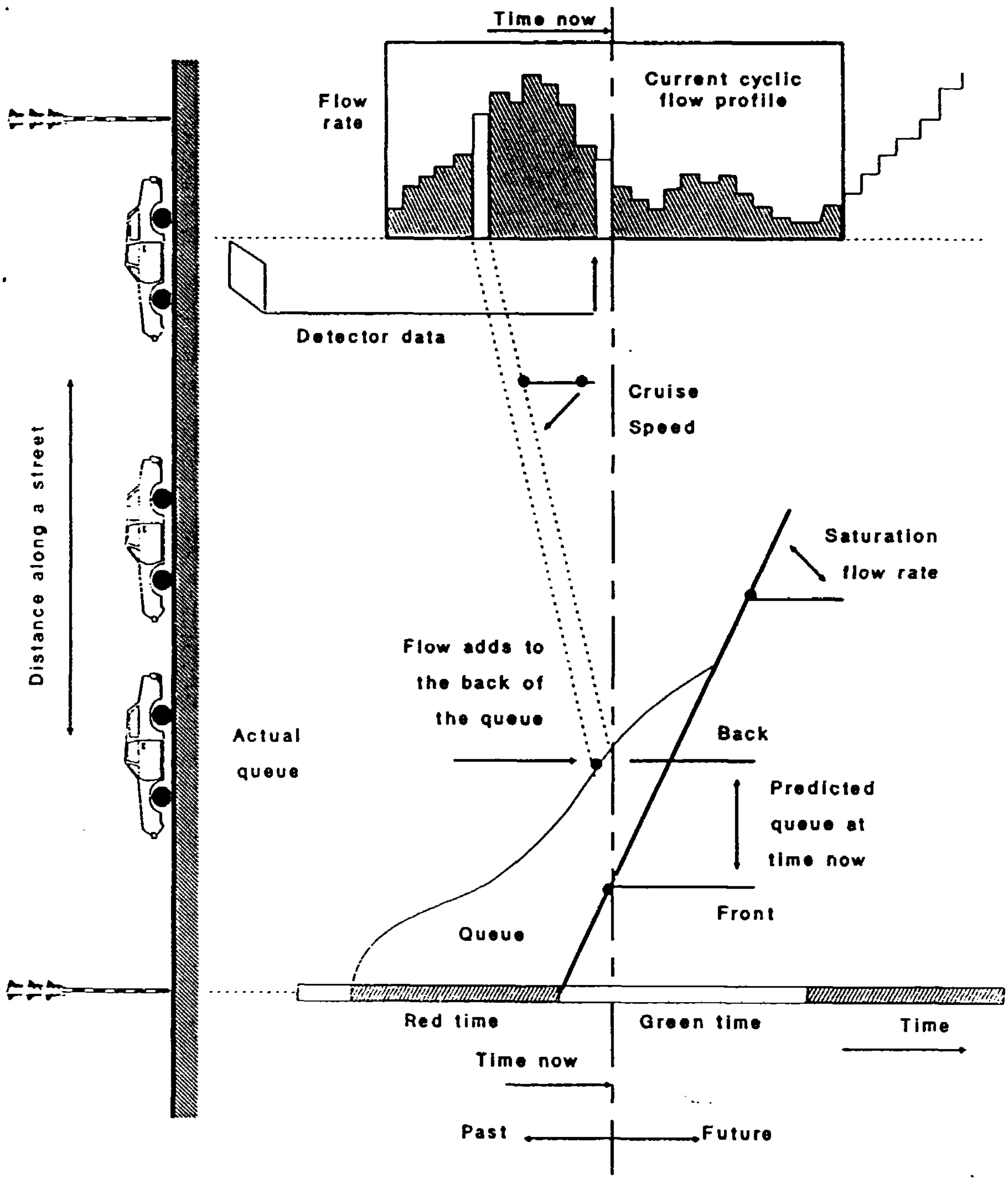

Figure 3.4 Principles of the 'SCOOT' traffic model

(Source: Reference 121)

4) The loop detectors utilized by third generation technology give only limited information on network traffic conditions. Externally-linked route guidance systems offer much greater feedback on signal plan performance, in the form of actual journey times and delays as they occur.

5) While in many ways, the second generation SCATS system is a tool no better than the engineers who set it up, SCOOT's use of an on-line traffic model makes it into a black box you either love or hate. Recent development of SCOOT "procedures" has led to traffic management techniques which work essentially by fooling the model. A fourth generation system would contain explicit, policy-related intervention strategies for use by highway agencies, or by a higher-level expert system.

Table 3.1 summarizes the advantages and disadvantages of current approaches to UTC. Traffic adaptive systems are more costly to install than purely fixed time systems. However, the additional benefits demonstrated by advanced systems can justify the cost within a short period. In the short-term, fixed-time and responsive systems can operate signals in adjacent parts of urban areas. Adaptive systems may give greatest returns in CBDs where congestion is high and flow patterns are complex, varying from day-to-day. Fixed time control will work well where congestion is lower and flow patterns more consistent.

3.3 Incident detection systems

Another category of advanced technology systems included in this review is that of automatic incident detection systems. Incidents such as accidents or queue formation behind slow-moving vehicles can rapidly cause significant congestion problems, particularly on freeways. Techniques are now becoming available which will automatically detect incidents, allowing adjustments to be made to traffic control strategies and enabling information to be passed to drivers through many other technologies.

Traffic incidents can generally be divided into recurrent and non-recurrent problems. Recurrent problems occur routinely during peak periods when traffic demand exceeds capacity, even for relatively short time periods. Peak-period congestion occurs daily and is reasonably predictable in both effect and duration. Nonrecurrent problems are caused by random, unpredictable incidents such as traffic accidents, temporary freeway blockages, maintenance operations, oversize loads, etc. Environmental problems such as rain, ice, snow and fog also fall into this category [122, 123].

Automatic incident detection systems typically consist of a small computer or distributed microprocessor system, monitoring signals from vehicle detectors spaced along the highway. Special algorithms are used to detect incidents by looking for particular disturbances in traffic flow patterns.

A number of operational automatic incident detection systems have been implemented in the U.S. The most important of these is in use on the Chicago

Type of UTC system	Advantages	Disadvantages
Fixed time	* Cheaper to install and maintain. * Can be implemented using non-centrally controlled equipment. * Familiarity with settings for regular users. * 'Green waves' easily implemented.	* Needs large amounts of data to be collected and updated. * Signal plans will require updating. * Disruption of plan changing. * Requres operator reaction to incidents. * Cannot deal with short-term fluctuations in flow levels.
Partially adaptive	* Can deal with some day-to-day fluctuations. * Plan change time may be more appropriate. * Might be valuable on arterial routes. * May be cheaper than fully responsive control as fewer detectors required.	* Requires as much or more data to be collected as for fixed time sytems. * Detector failure possible. * Needs decisions on thresholds for plan change. * May plan change for wrong reason. * Difficult to foresee all plan needs.
Fully adaptive	* Less data need to be collected in advance. * Plan evolves so avoids problems with plan changing and updating. * Can deal with short and long-term fluctuations in flow levels. * Automatic reaction to incidents. * Monitors traffic situation throughout the area.	* Detector failure possible. * More expensive to install. * Requires central control. * Maintenance critical.

Table 3.1 Summary of the advantages and disadvantages of different types of UTC systems

freeway system. In the Chicago area, loop detectors are provided in each lane every three miles along the freeway. Flow is also sampled in one of the center lanes at half-mile intermediate points. All ramps are monitored to produce a closed subsystem every three miles. The actual field location of detectors usually depends upon the availability of utility service, often most readily available around urban interchange areas. All surveillance and control points in a particular service area are brought to a roadside cabinet, through aerial or underground interconnect systems [124]. These are connected in turn to a surveillance center.

In Europe, different algorithms have been developed for incident detection. HIOCC, for example, operates by identifying the presence of stationary or slow-moving vehicles over individual induction loop sensors. This is achieved by looking for several consecutive seconds of high loop occupancy. An alarm is initiated when this is detected.

In the U.K., an experimental incident detection system was initially installed on the M1 and M4 motorways. Seven monitoring loops were cut into the pavement surface at intervals of 1600 feet, and preliminary investigations enabled improvements to be made in the system [125]. Based on these trials, a commercial system based on HIOCC is now available from the Golden River Corporation known as GRID (Golden River Incident Detection) [126] (Figure 3.5). Since these initial developments, the scheme has been extended to cover 50 miles of the congested M1 motorway [127] (Figure 3.6).

In West Germany, incident detection equipment has been used to alert motorists of the formation of queues at an autobahn bottleneck [7]. Inductive loop detectors are used to record traffic volume and vehicle speed data for analysis at a control center. If the traffic data reveal that a performance threshold has been passed, an automatic queue warning is given to approaching vehicles via variable message signs, and successively lower speed limits are set. This gradually reduces the speed of traffic nearing the queue, decreasing the danger of rear-end collisions.

Systems for detecting adverse environmental conditions are a second type of automatic incident detection system, which could also potentially be linked into a computerized monitoring network. There are a number of commercial sensor systems available, such as those manufactured by SCAN of St. Louis, SFG in West Germany and ELIN Electronics in Austria [128, 129, 130].

The most significant implementation of an integrated system to date has taken place on the Dutch freeway system. Here electronic roadside sensors that automatically detect dangerous road conditions likely to cause accidents and congestion were installed in 1985 (Figure 3.7). These are capable of remotely detecting pavement slickness due to rain, snow, ice, sleet or commodity spillages. Variable message signing is linked to the sensors to direct drivers to slow down as necessary [132, 133, 134].

Another operational example of the use of incident detection to warn of adverse environmental conditions is in West Germany, where fog warning systems have been installed at several locations [7]. These are used on autobahns where fog occurs

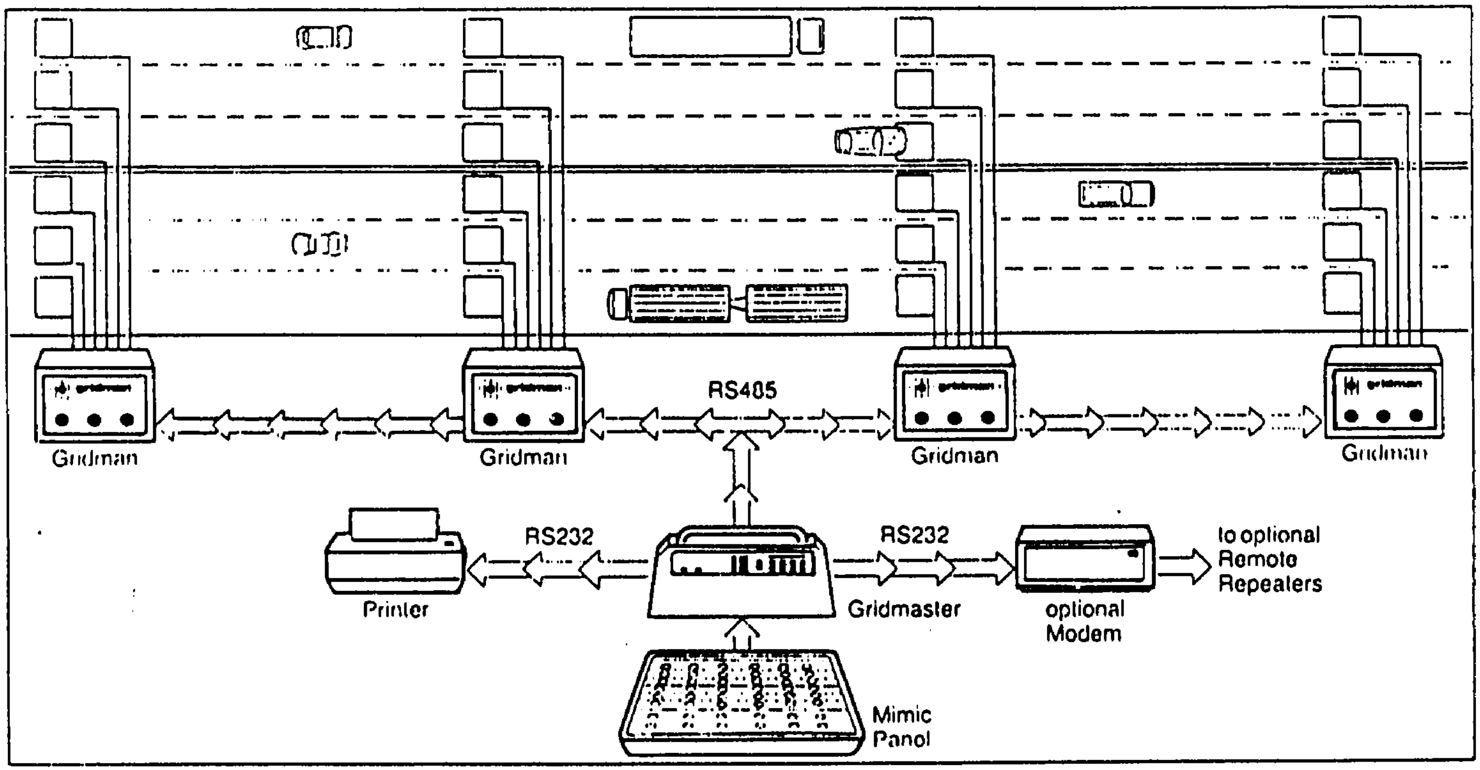

Figure 3.5 Grid Incident Detection System

(Source: Reference 126)

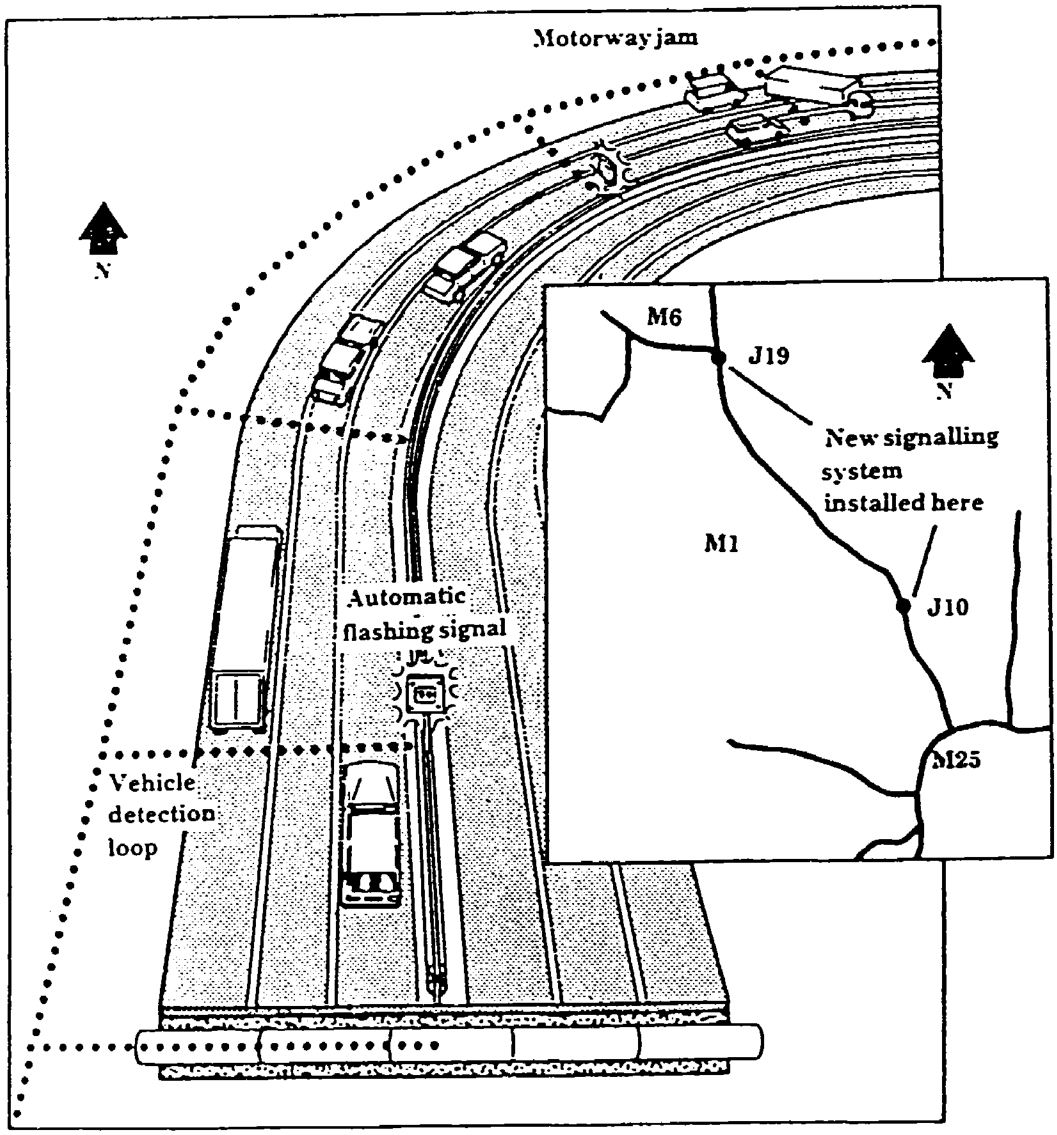

Figure 3.6 Incident detectionsystem, M1 motorway

(Source: Reference 127)

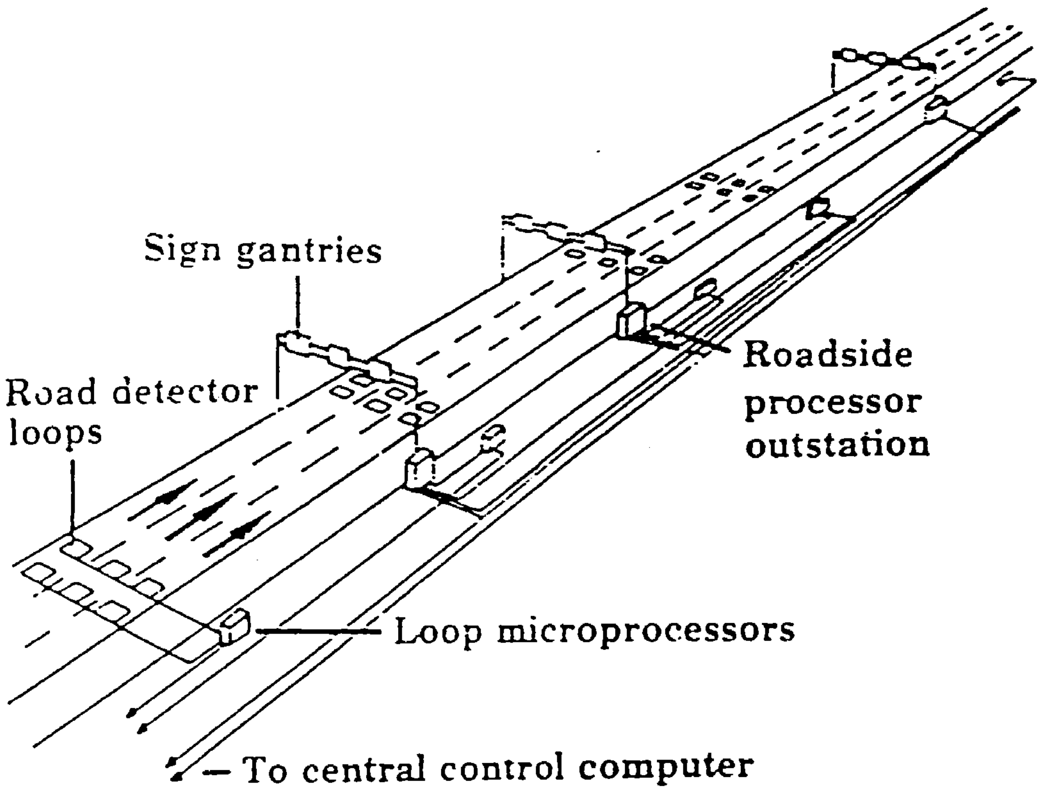

Figure 3.7 Rotterdam's motorway control and signalling system

(Source: Reference 131)

frequently and rapidly, often over localized areas. The equipment uses sensors to continuously measure the range of visibility. This information is relayed to a control center and compared with a threshold. Where poor visibility is detected, the roadside variable message signs and hazard warning lights are activated as a means of providing advance warning. Variable message signs are also used to display successively lower speed limits on the approach to the affected area.

3.4 Freeway and corridor control

Freeway management techniques fall into two main categories: capacity management and demand management [135]. Capacity management seeks to maximize throughput and improve the level of service, while demand management attempts to reduce the vehicle miles traveled or encourage off-peak travel. Examples of capacity management include ramp closures, ramp metering, variable speed control, lane control, express or reversible lanes, etc. Demand management techniques include staggered or flexible working hours, ridesharing, and improved public transit.

Ramp control aims to limit the rate at which vehicles enter the freeway, in order to avoid overloading the facility. Ramp closures are the simplest and most drastic form of ramp control. However, because of public opposition, ramp closures are not widely used in the U.S. [136, 137], though they are routine in Japan [138, 139].

Ramp metering [140] is more widely utilized, and may have greater potential for interfacing with advanced traffic control technologies. A standard traffic signal is used to control entry to the mainline. In the U.S., a single vehicle is commonly released per green, while in Europe, operation resembles conventional signals with longer green and red periods. Chicago was the first metropolitan area to practice ramp control in 1963 [141]. Ramp metering signals now control traffic at 91 locations along various Chicago-area expressways. Centrally timed by the traffic systems center computer at Oak Park, the ramp signals are varied continuously as measured ramp and mainline flows are monitored in real time. The total instrumented network covers 110 highway miles, with 1650 loop detectors.

Evaluations of ramp metering in Chicago found that the technique reduced peak period congestion by up to 60 percent and accidents by up to 18 percent [142]. Benefits will vary according to the level of congestion prevailing before the implementation of controls [143]. On Houston's Gulf Freeway, for example, travel times were reduced by 25 percent and accidents by 50 percent, with little adverse effect on adjacent arterials. Many other North American cities report favorable experiences from implementing ramp control [144, 145, 146, 147].

Ramp metering has also been experimentally implemented on the M4 motorway in Birmingham, U.K. A signal control algorithm responds to speed and flow data received from detectors located on the ramp and in the motorway lanes. Capacity downstream of the intersection is monitored continuously to allow metering rates to be adjusted in line with current conditions. The system is activated automatically in response to traffic conditions and remains in operation throughout the morning peak. Traffic on the ramp is given a green signal unless the combined ramp and motorway demand flow exceeds a critical limit, or traffic speeds at the intersection fall below a preset threshold.

Mainline control of speeds using variable message signs has been implemented in Britain, the Netherlands, Germany, Italy, Japan and the U.S. Speed advisories can be used to give advance warnings of traffic incidents or fog ahead. In Holland, they are also used to help smooth peak traffic flows. Elsewhere, they have been less successful as a capacity-enhancement measure; drivers in both Britain and the U.S. commonly ignore advisory speed limits [148, 149, 150].

Lane reversal for tidal flow operation is implemented both on freeways and arterials in many countries. In the U.S., reversible lanes are often indicated by permanent signs and lane markings alone, relying on drivers to observe time-of-day limitations. In Europe, variable message signs are almost always used for permanent tidal flow control, with overhead gantries and advanced warning signs which are electronically switched at the appropriate times.

Traffic control centers are a vital requirement for integrating advanced technologies to improve conditions on urban freeways. Washington State Department of Transportation, for example, has had a freeway control center in operation for over 10 years. This is capable of monitoring flows, through a system of traffic detectors and data links. Virginia Department of Transportation also has a freeway control and monitoring system in operation. The Traffic Management System (TMS) is a computerized freeway surveillance and control system that monitors and regulates traffic flow along Interstate 395 and Interstate 66. Traffic flow data is gathered by 550 traffic counters imbedded in the pavement of interstate lanes and entrance ramps. Current mainline traffic and incoming demand are balanced with the known capacity of the freeway using ramp metering. The Virginia DOT system also includes variable message signing for communicating with drivers.

Typical European practice in control center and communications design, including closed circuit television, emergency telephone and radio systems, signalling, and maps has been set out in a U.K. Home Office publication [151]. British freeways are controlled from five regional computer centers over the National Motorway Communications System (NMCS-2), which links emergency telephones every mile and variable message signs at least every two miles. Traffic speeds and flows are continuously recorded and meteorological conditions monitored from roadside outstations [152].

Corridor control is a concept which seeks to treat urban freeways and adjacent arterials as a single system. The purpose of corridor control is to optimize the use of corridor capacity by diverting traffic from overloaded links to those with excess capacity. Currently, several corridor control projects are being developed, tested and evaluated [145, 153, 154, 155].

3.5 Interactive signal coordination

Interactive signal coordination is a new concept which may constitute the next generation of traffic control systems. It would go further than adaptive traffic control, in that it would be fully responsive to the actual pattern of short-term future travel demand, and would integrate traffic control systems with other advanced technologies. For example, an interactive system could be linked with real-time traffic monitoring, short-term forecasting and electronic route guidance. Using data on actual vehicle destinations, it would then simultaneously optimize signal coordination and vehicle route choice within the urban highway network.

Interactive signal coordination is still at the stage where ideas and concepts are being synthesized. Therefore, a definitive concept for an interactive traffic control system has not yet been developed. However, a series of possible aims has been identified, including:

* Minimize vehicle delays;
* Minimize passenger delays;
* Minimize variability in transit times;
* Minimize user costs;
* Minimize negative environmental impacts;
* Minimize unnecessary travel; and
* Maximize safety of the system.

In order to accomplish these objectives and address the shortcomings of existing control systems, a series of features that could be included in the fourth generation traffic control systems have been proposed. These include:

* Integration of traffic signal control systems with other advanced systems, leading to coordinated control of a number of different systems.
* Prompt detection of and response to events.
* Ability to predict and respond to origin-destination information.
* Integration with vehicle location, identification, and classification systems.
* Inclusion of artificial intelligence and expert system features.
* Accommodation of demand control and congestion pricing options.
* Flexibility to accommodate different control objectives in different parts of an urban area or during different time periods.
* Real time communications with motorists.
* Inclusion of visual surveillance.

* Variable speed control to determine appropriate speeds during periods of congestion and inclement weather.

* Provisions for integration with automatic vehicle control.

3.6 Summary

Advanced traffic control systems are further developed than the information technologies reviewed in the previous chapter. Control of traffic in time as well as space adds a fourth dimension to conventional highway engineering solutions to the congestion problem. The proven benefits of these systems include freer traffic flows, shorter journey times, substantial fuel savings, and generally reduced congestion.

Signalization strategies include improved methods of isolated intersection controls and fixed time coordination; partially and fully adaptive coordination; and new concepts for fourth generation, expert systems control. Incident detection systems may in future be integrated with other advanced traffic control techniques, within freeway corridors and in due course throughout entire metropolitan areas. Finally, interactive traffic control concepts seek to integrate the driver information systems discussed in Chapter 2 with the traffic control systems of this chapter.

4. ADVANCED VEHICLE CONTROL SYSTEMS

4.1 Introduction

Advanced vehicle control systems (AVCS) can help drivers to perform certain vehicle control functions, and may eventually relieve the driver of some or all of the control tasks. The use of AVCS technologies is likely to result in greater safety, more consistent driver behavior and improved traffic flow characteristics.

Vehicle control is complex because of the large number of interactions which exist between the driver and the vehicle. The driver's key roles can be defined as:

* to observe the outside environment, including highway geometry, vehicles and obstructions;

* to operate the vehicle's control system;

* to feedback observations and compensate for changing situations; and

* to make decisions and select an appropriate trajectory ahead.

On a journey a driver is constantly required to assess vehicular lateral position, speed, distance to vehicles ahead and judge gaps for merging and passing. Additionally, the driver must also anticipate the actions of other road users and make decisions on opportunities for getting through lane changes, merges, and intersections by achieving smooth braking and acceleration.

At the most basic level, AVCS can provide the driver with useful information and warnings, based on data collected by onboard sensors. The next stage is to assist the driver with the control process, by automatically adjusting the control system characteristics to the operating conditions and helping to avoid situations which give rise to loss of control. The third level is to allow the control system to intervene and manage critical situations. The highest level is for the system to completely take over the driving tasks.

This chapter provides an overview of AVCS concepts. It examines the AVCS technologies currently available, and considers the more widespread uses of these systems in the future. It outlines the systems which are presently under development and considers the feasibility of implementation of these technologies.

4.2 Antilock braking systems

The Antilock Braking System (ABS) assumes control of the braking function during periods of excessive braking or cornering. ABS differentially pumps the brakes to ensure rapid, non-skid braking. This is performed by a solenoid valve unit which connects the master cylinder and the wheel cylinder, and is controlled by an electronic control unit.

To the driver, the benefit of ABS is the ability to remain in full control of the vehicle under every type of road condition and during emergency stops. Without ABS, once the front wheels lock in an emergency stop it becomes impossible to steer the car. Similarly if the rear wheels lock, the car becomes unstable and is prone to skidding. Wheel lock also reduces the effect of the braking action. There are several proprietary antilock braking systems now available, such as those marketed by Scania [156] and Alfred Teves [157].

The widespread implementation of ABS could reduce the number of accidents involving skidding. According to one survey, 13.5 percent of all injury accidents involve some form of skidding [158]. Investigations suggest that over 7 percent of all road accidents might have been prevented if ABS had been fitted to the vehicles involved [157].

Another technology that can be incorporated with ABS is Electronic Traction Control (ETC), also known as slip-spin control. This utilizes the same sensors and computer that prevent the wheels from skidding during braking to prevent the wheels from slipping during acceleration.

When a vehicle is accelerating on a surface with a low coefficient of friction, opening the throttle too wide will cause the wheels to spin. The wheels are then no longer able to transmit lateral force, causing the vehicle to become unstable. Using ETC, sensors detect when the wheels are about to start spinning, and prevent this from happening by reducing engine torque or partially applying the brakes.

4.3 Speed control systems

Speed control systems are an essential component of AVCS technology. Two types of speed control systems are available on present generations of vehicles. These are cruise control and governors.

Cruise control [159] is one form of speed control technology that is already in widespread use in the U.S. In normal operation, the cruise control maintains the speed of the car, set by the driver, until a new speed is selected or the brake pedal depressed. The cruise control can also permit controlled acceleration and deceleration, and can resume to a speed stored in the memory following a braking incident.

The European PROMETHEUS program is currently examining the feasibility of developing cruise control systems capable of responding to external vehicle sensing devices. This concept, called "Intelligent Cruise Control", aims to develop techniques to process sensory information for the control of vehicle speed [160]. In the most sophisticated form, it may be feasible to interpret sensor information on road and traffic conditions, speed of other vehicles, obstacle detection and forward visibility and to adjust the speed accordingly. Preliminary research indicates that a prototype system capable of operating in a well-structured environment could be demonstrated in the near term, given required progress with sensor technology research.

A second speed control technology already available, though not widely utilized, is the speed governor. Governors are limiting devices which prevent a vehicle from exceeding a pre-set speed limit. They have mainly been used on heavier vehicles, such as trucks and buses, powered by diesel engines. When the vehicle exceeds the preprogrammed speed, a signal is triggered which acts on the fuel injection pump to prevent further acceleration.

4.4 Variable speed control

A natural extension of current speed control systems would be variable speed control (VSC), for which the component technologies largely exist. Systems which vary vehicular speed automatically or provide the driver with information for optimal speed adjustment have the potential to reduce speed differentials and minimize the frequency of vehicle stops.

The simplest form of VSC would program conventional cruise controls or governors with mandatory fixed speed limit information appropriate to each section of highway. This could be readily accomplished using existing AVI technology described in Chapter 2. Another option is to locate reference markers such as electronic chips or small permanent magnets at variable spacings in the traffic lane so as to indicate safe speed by marker spacing.

In a second stage of application, variable-message speed control signs similar to those widely utilized on European freeways could be linked by AVI to an onboard VSC. Equipped vehicles would automatically select the safe operating speed for each section of highway, which could be optimized to suit capacity considerations or lowered under adverse weather conditions.

The aim of VSC at traffic signals would be to assist the driver in selecting a suitable speed on the approach to an intersection so that the vehicle would not need to stop. Advisory roadside speed control signs have been utilized for many years in West German traffic control systems, informing drivers of the optimal cruise speed to reach the next signal at green.

More recent research in West Germany has led to the development of an in-vehicle speed advisory system at traffic signals [7]. Infrared beacons installed at intersections are used to transmit signal timing information to approaching vehicles equipped with a suitable onboard receiver. The recommended speed is indicated by green light points which are integrated within a conventional speedometer. The system has been developed and tested jointly by Volkswagen and Siemens, and is currently being investigated further as part of the PROMETHEUS program.

Each of the three applications of VSC outlined in this section could be operated in an advisory mode or an automatic mode linked to cruise or governor systems controlling the vehicle's throttle setting. The automatic mode could be user-selectable, allowing drivers to override the system, or could be mandatory, requiring vehicles to comply at all times. The mode of operation could also be varied on different types of highway, so that mandatory speed control might be required for drivers to be allowed to use certain high-capacity, limited-access facilities comparable to current HOV lanes.

4.5 Automatic headway control

A natural extension to intelligent cruise and variable speed controls is the addition of sensors to automatically maintain a constant headway or gap between vehicles. The essential elements of an automatic headway control (AHC) system are a distance monitoring system, signal processing, control logic and speed regulation through throttle and brake control. The block diagram in Figure 4.1, from a paper by Grimes and Jones [161], shows a radar headway control system based on cruise control technology. When fitted with an AHC device, a vehicle would automatically slow when approaching a vehicle, and remain at a safe distance until such time as it was appropriate to resume the original cruise speed. This feature would be particularly useful for urban freeway driving.

Papers by Hahn [162] and Belohoubek [163] concentrated on AHC system with automatic throttle control only. Belohoubek describes a system which utilizes a microprocessor to monitor ground speed and radar signals reflected from the vehicle in front. Throttle control is achieved by means of a linear DC motor connected by a chain, which receives instructions from the microprocessor in the form of variable-width pulses. The system does not incorporate automatic brake control, deceleration being achieved by air friction and engine drag when the throttle is released. If more rapid deceleration is required, an audible warning advises the driver to brake manually.

The European PROMETHEUS program has defined several relevant research topics within the AHC area. Lissel [164] outlines the development of a headway control distance sensor to enable drivers to maintain a safe driving distance in front of the vehicle. Cloup [165] describes another research topic within PROMETHEUS to analyze and interpret sensor outputs for an anticollision radar. The objective is to calculate the relative speed and distance of the object and, using the vehicle's speed, to determine the likelihood of a collision. The output can then be fed to a decision system for appropriate action to be taken.

PROMETHEUS has also defined a research project aimed at improving the reliability of radar sensors [166]. The project will involve the use of a video camera as well as a radar system to enable headways to be deduced. Another project within PROMETHEUS is outlined by Bray [167]. The aim is to determine and track the presence of a leading vehicle, using a pair of stereo cameras. Similar developments aimed at vehicle steering using existing roadway lane markings are also understood to have begun recently within the Texas state IVHS program.

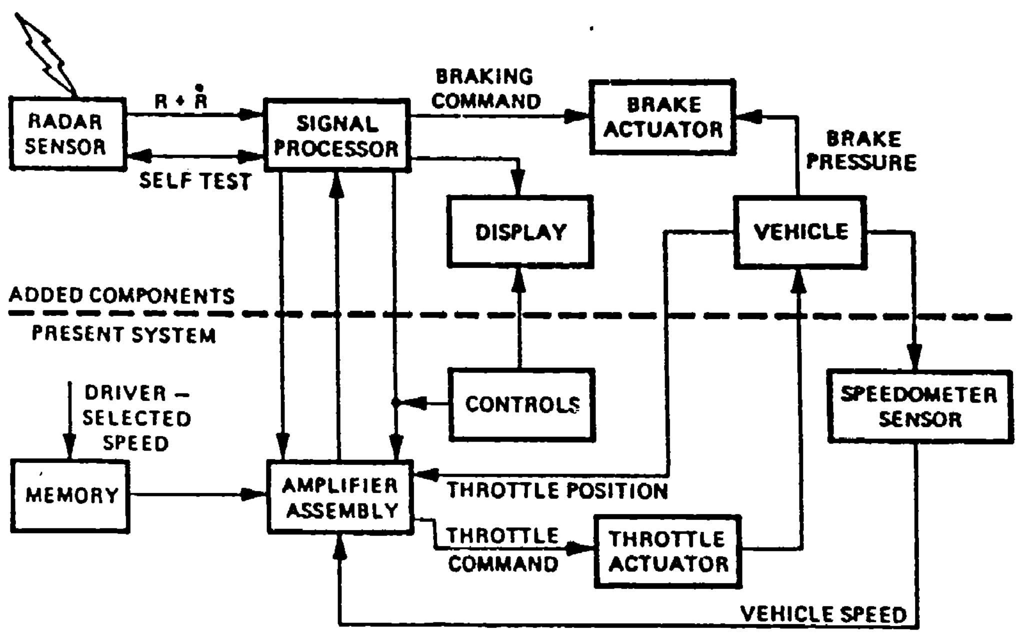

Figure 4.1 Block diagram of an AHC System

(Source: Reference 161)

4.6 Collision warning systems

The major cause of collisions, on all types of highway, results from an inability of some drivers to correctly judge speeds and distances. This is especially true in bad weather conditions and at night. A system which warns drivers that they are driving too fast or too close, or, in the event of an impending collision, automatically applies the brakes, could significantly reduce this type of accident, and provide an associated reduction in congestion.

One such collision avoidance system that has been extensively investigated is automatic braking using radar detection. Brinton [168] describes an early system which used doppler radar. Further work has been carried out in this area by researchers such as Flannery [169], Troll [170], and Grimes and Jones [161].

Radar braking operates by detecting the presence of an obstacle in front of the vehicle, such as another vehicle or a pedestrian, using a radar head fitted to the front of the vehicle. From these raw data, a signal processor calculates the range and relative velocity of the vehicle and the object. Various processing techniques have been developed to perform this function. Long-range radars use one of two methods for range calculations; pulse modulation or frequency modulation. Short-range radars can also use these techniques, or may alternatively be based on the diplex Doppler method or sinusoidal frequency modulation.

Having received and analyzed the range and relative velocity, the signal processor is fed further data relating to the vehicle's ground speed and the present state of braking. This is analyzed and compared with the range and relative velocity. The processor utilizes internal logic to decide if the target is real or false and, in the event of a collision being deemed probable, actuates the brakes.

One of the main problems of radar braking is false alarms. False alarms may be caused by roadside obstacles, such as trees, signs, fences or parked cars, or by vehicles in different lanes or traveling in different directions. Obstructions in the roadway must be separated into major items and inconsequential items. Systems are particularly vulnerable to false alarms at corners or bends, where a roadside obstacle or vehicle may appear to be in line with the direction of travel. This problem may be reduced by limiting the range of the radar, although this also reduces efficiency at high speeds.

Another major problem with radar braking is that of 'blinding'. This occurs when radar signals from vehicles traveling in the opposite direction block out the return signals from potential obstacles. There are also certain problems associated with radar braking systems caused by poor weather conditions, with the most serious problem being backscatter from rainwater.

While a number of manufacturers and researchers have worked on radar braking, the problems described above have led many of these efforts to be abandoned. However, a radar-based collision avoidance system that may represent the state-of-the-art in this area is currently being tested in California as part of the PATH (Program on Advanced Technology for the Highway) initiative [171]. The system has been developed by Radar Control Systems Corporation, and responds to changes in the speed of a moving vehicle ahead of the equipped car. A radar antenna mounted on the front of the vehicle broadcasts a low power radar signal which is reflected back from the leading vehicle. An in-vehicle unit processes the signal and detects whether the speed of the leading vehicle is changing. Where hazards are detected, the driver is advised to reduce speed using a warning voice or head-up display. The system can also include an override function to automatically brake the vehicle when required.

Another type of radar-based collision avoidance system developed in the U.S. is GM Delco's Near Obstacle Detection System (NODS) [171]. This uses microwave radar and continuous Doppler technology to detect objects within an area behind the vehicle. Future versions of the system will also include side and blind spot obstacle detection. GM's research laboratories are additionally working on a project known as the Highway Driver's Assistant (HDA). The HDA vehicle integrates AVCS technologies such as lane sensing, hazard warning and headway control with navigation, route planning and real-time traffic information facilities.

4.7 Automatic steering control

Automatic steering control (ASC) systems linked to power assisted steering can ensure vehicles follow a pre-determined path along dedicated highway lanes. Automatic steering control systems must possess three essential constituents:

1. A roadway reference system, which can be sensed by a vehicle in order to ascertain its lateral position relative to the highway.

2. Onboard sensors which measure the lateral displacement and determine any necessary remedial action.

3. A steering control system which acts automatically on command signals to maintain or adjust the lateral position as required.

Techniques for achieving lateral position control can be categorized into two groups: those systems which require passive roadway reference systems, and those using active reference systems.

A **passive reference** is an inert structure or component of the guideway, such as a metalized strip, painted stripe, passive reflectors, or a sidewall. Each vehicle obtains its own positional information using onboard equipment to detect this inert reference. One particular type of passive system that has been considered by Mayhan and Bishel [172] utilizes radar and a reference system in the form of a fixed barrier at the side of the roadway to obtain the necessary information for lateral control. A possible configuration is shown in Figure 4.2

An **active reference** is used in the second type of ASC system to provide the information required for lateral position control. This typically involves the use of an energized cable running along the desired vehicular path, usually buried below the pavement surface.

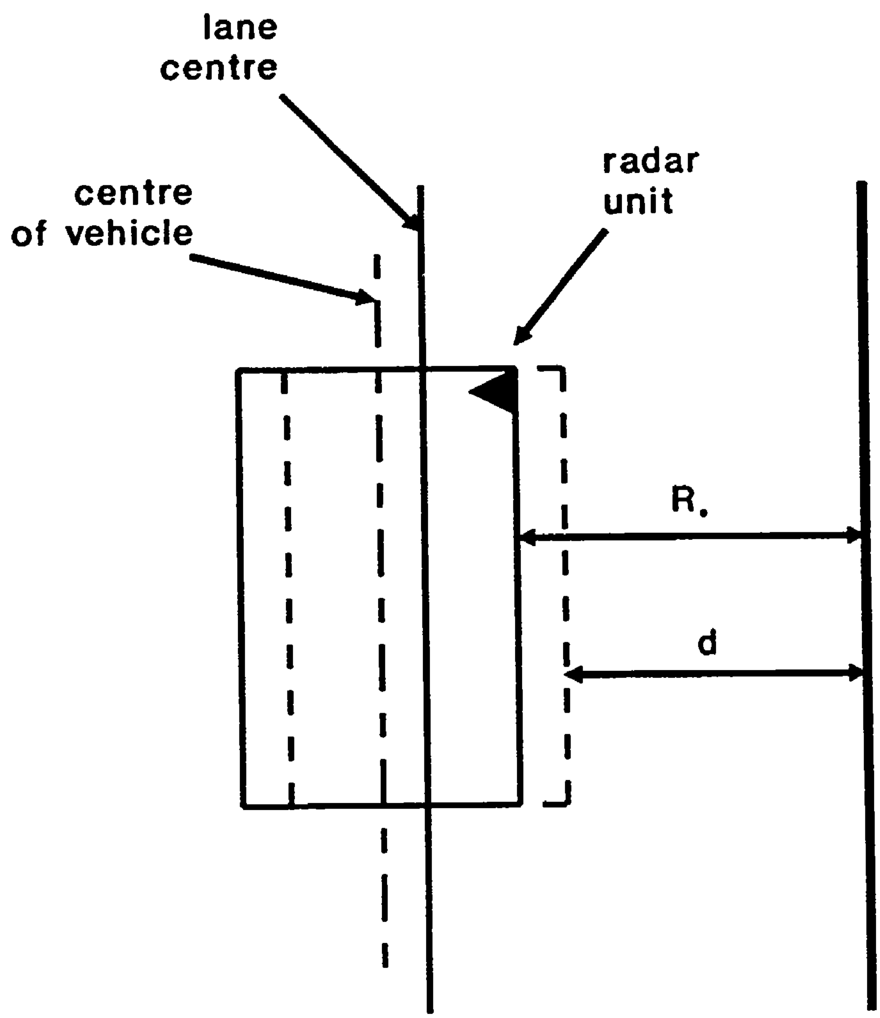

Figure 4.2 Vehicle-borne radar for lateral control

(Source: Reference 172)

During the late 1950s, General Motors and RCA developed and demonstrated automatic control of steering and longitudinal spacing of automobiles [173] for what was called the "Electronic Highway". By 1962, the first university research on automatic steering control of automobiles was reported from Ohio State University [174], under the sponsorship of the Ohio Department of Highways and the Bureau of Public Roads. This led to a later, long-term control study, under the sponsorship of the Ohio Department of Transportation and the Federal Highway Administration between 1965 and 1980. The first broad-scale investigation of the application of automation technologies to urban transportation problems appears to have been in the M.I.T. Project METRAN, in the spring of 1966 [175].

The basis of this type of system was that a buried energized cable created a magnetic field which was sensed by equipment under the vehicle [176]. Deviations from the cable centerline produced a positive or negative dc error signal, depending on the direction, which was approximately proportional to the lateral displacement (Figure 4.3). The error signal was fed into a stabilizing circuit and the resulting signal used to operate the vehicle's steering.

A major problem with energized wire reference following systems is that of interference on reinforced concrete pavements, where steel reinforcement causes the magnetic field to be weakened and distorted. This leads to a disturbed ride, and in extreme cases could result in a total loss of lateral control.

4.8 Automated highway system

This final section deals with the most complex and ambitious form of AVCS: the automated highway system (AHS). The previous technologies assisted or assumed the role of the driver in performing one particular function, such as steering or braking. On an automated highway, however, vehicles would be totally automated in all aspects of control by a combination of these technologies, suitably adapted to an environment of total vehicle control.

The basis of the AHS is essentially vehicle control in two directions - longitudinal and lateral [177]. Incorporated with this must be an ability to merge streams of vehicles, allowing vehicles to enter and exit the AHS at appropriate intersections, as well as providing for breakdown and emergency facilities.

Two approaches for achieving longitudinal control have been advocated: synchronous, or asynchronous. The synchronous concept, also referred to as synchronous longitudinal guidance (SLG) or point-following, may be compared to a conveyor belt, divided into equal slots [184]. Each controlled vehicle is assigned a slot, and obtains reference information in order to determine its position relative to that slot. Reference information may be provided by one of two methods: either through the use of roadway or roadside position reference benchmarks, or through the use of a continuous signal moving at synchronous speed.

The asynchronous technique, sometimes referred to as the car-following approach, does not confine a vehicle to a moving slot, but rather controls a vehicle on the

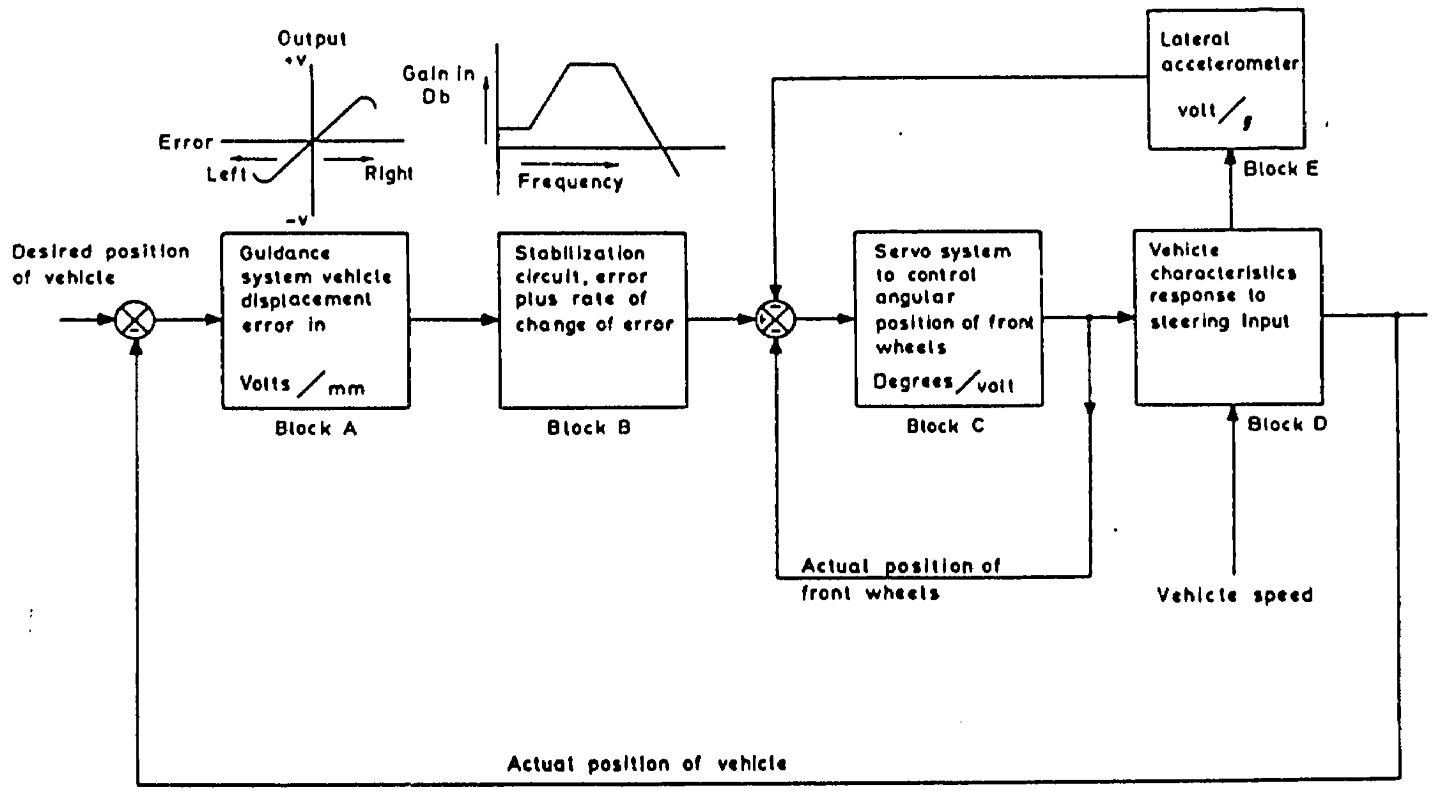

Figure 4.3 Operating principle of steering control system

(Source: Reference 176)

basis of its state and that of the other traffic [179]. An example of the asynchronous concept, in which the control of a following vehicle is determined with respect to a leading vehicle only, is the use of AHC.

Although basic lateral and longitudinal control systems constitute the essential elements of an AHS, equally important is the ability to successfully merge vehicles into a controlled traffic situation. This might be achieved using the lateral and longitudinal control systems, and has two major aspects; the macroscopic or systems aspect, and the microscopic aspect.

The macroscopic aspect is concerned with the simultaneous merging of a large number of vehicles at many intersections, and the resulting effects on system performance. The microscopic aspect is concerned with the control of a particular vehicle during an automated merging maneuver.

Another important consideration is the control of vehicles entering and exiting the automated stretches of highway. An entering vehicle would be operated in the manual mode on the approach to the AHS, until the entry point was reached. The vehicle would then be merged into a suitable gap and would continue under automatic control. Exiting the AHS would occur in the reverse fashion, with manual control being restored during the final stage of the exiting procedure.

Given the substantial alterations necessary to the present vehicle population and roadway infrastructure, rapid implementation of a full AHS may not currently be practical. A more promising approach could be a staged implementation in which total automation would be achieved following the introduction of several less radical changes. While implementation is gradually taking place, vehicles both equipped and unequipped with the new technologies would still use the same highways. This 'evolutionary' approach could essentially consist of three stages of deployment.

The first stage of the implementation would be the development and introduction of driver aids on a commercial basis. These would generally be vehicle-borne systems, requiring little or no support from roadside equipment. Several automobile manufacturers have already produced concept cars which incorporate collision avoidance radar. Metzler et al [180] described the features included in the Mercedes-Benz research vehicle in 1981. Ford's Continental Concept 100 in 1984 also incorporated a sonar detection system [181].

After a testing period, there may be sufficient acceptance or demand to permit the introduction of the second stage. This would involve the phased introduction of subsystems for partial automation. The adaptation of an existing highway lane in each direction, for example, could allow the introduction of ASC. Suitably equipped vehicles would now be able to utilize steering control in the modified lane, whereas those not equipped would still be able to use the other lanes.

Eventually, given the successful execution of stages one and two, there could come a time when most vehicles are fitted with automatic longitudinal and lateral control facilities. When this is the case, the third stage, the phased introduction of fully automated highways, could begin. This would be the most radical step of the implementation process, requiring major development and construction of control center systems and intervehicle communications.

One recently advocated approach that could ultimately lead to full automation through a staged implementation process is the advanced vehicle command and control system (AVCCS) concept [182]. An AVCCS would combine a number of technologies that are either already in use or currently under development. The primary components of the AVCCS are a distance measurement and direction sensing system, a radar-proximity detection system and a cellular communications system. Each of these elements could be introduced independently to provide valuable benefits, implying that full automation need not be achieved through one major step with its associated risks and uncertainties.

The AVCCS concept is based around a passive transponder technology which will be embedded at intervals in the pavement surface. This will provide vehicle-mounted receivers with information on location, heading and the distance to the next transponder. The transponders will also transmit maximum vehicle speed, minimum headway and other data that may be required by the onboard unit. Between transponders, the AVCCS will use a wheel sensor and magnetic compass for vehicle control, supported by the radar proximity detection system. This latter technology will monitor all four sides of the vehicle, with a moveable detector on the front of the vehicle to track the rotation of the steering wheel.

The AVCCS concept has been designed such that the system could operate on current vehicle chassis and frame technology, requiring no alteration for the system to be fully functional. However, some alterations would be required to integrate the command and control system, to interface with the braking and steering, and to incorporate a route guidance capability. The degree of control provided by the AVCCS would be dependent upon the roadway's functional classification. On local streets, for example, only the navigation and collision avoidance functions would operate, while full automation would operate on limited access highways.

4.9 Summary

AVCS technologies seek to assist drivers in performing some or all of the driving tasks. Widespread use of AVCS could results in greater safety, more consistent behavior and improved traffic flow characteristics. At the most basic levels, AVCS can provide the driver with useful information and warnings. The next stage is to assist the driver directly, helping to avoid potentially dangerous situations. The third level would provide for system intervention through emergencies, while the final level would completely take over the driving task. Though AVCS are least developed of the IVHS technologies, their potential for relieving urban traffic congestion and improving rural safety could be very high.